

Antineutrino Oscillation Results from MiniBooNE & Implications for Future Experiments

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January 14, 2011

Outline

- Introduction
- LSND $\nu_\mu \rightarrow \nu_e$ Oscillation Results
- MiniBooNE $\nu_\mu \rightarrow \nu_e$ Oscillation Search
- MiniBooNE $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Oscillation Search
- Fits to the World Antineutrino Data
- Testing LSND/MiniBooNE Signals with Future Experiments (MINOS, NOvA, IceCube, BooNE, etc.)
- Conclusion

Neutrino Oscillations

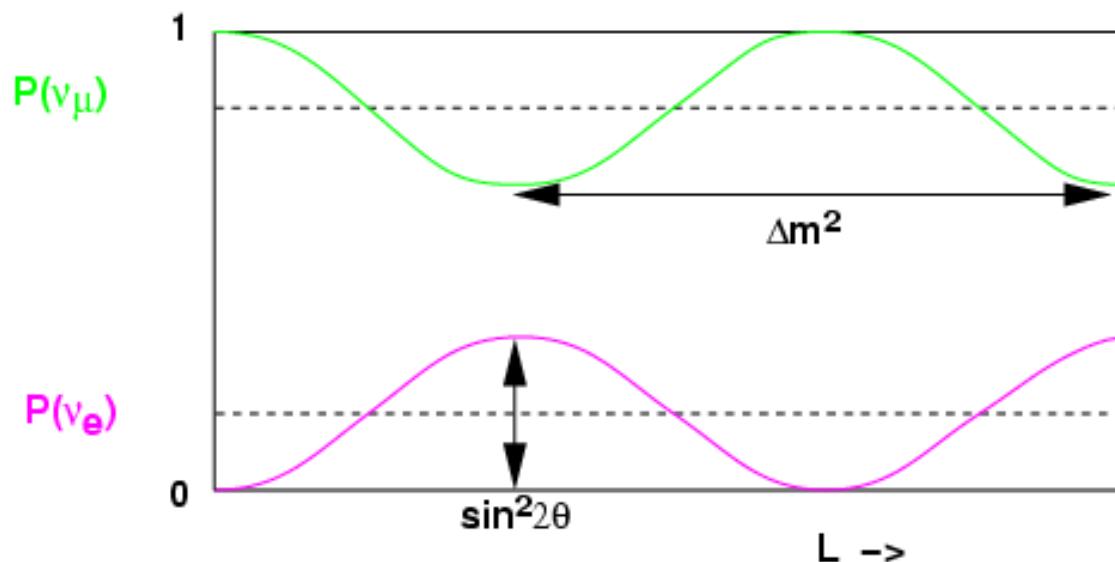
Weak Eigenstates

$$\nu_\mu \\ \nu_e$$

=
=

Eigenstates of Propagation

$$\cos\theta \nu_1 + \sin\theta \nu_2 \\ -\sin\theta \nu_1 + \cos\theta \nu_2$$



$$P_{\nu_\mu \rightarrow \nu_e} = \sin^2(2\theta) \sin^2(1.27 \Delta m^2 L / E_\nu)$$

$$\Delta m^2 = m_2^2 - m_1^2 \text{ in eV}^2, \text{ L in meters, } E_\nu \text{ in MeV}$$

Probability of Neutrino Oscillations

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4 \sum_i \sum_j |U_{\alpha i} U_{\beta i}^* U_{\alpha j}^* U_{\beta j}| \sin^2(1.27 \Delta m_{ij}^2 L / E_\nu)$$

As N increases, the formalism gets rapidly more complicated!

N	# Δm_{ij}^2	# θ_{ij}	#CP Phases
2	1	1	0
3	2	3	1
6	5	15	10

T & CP & CPT Violation in the Lepton Sector

$$\nu_\alpha \rightarrow \nu_\beta \neq \bar{\nu}_\beta \rightarrow \bar{\nu}_\alpha$$

T Violation

$$\nu_\alpha \rightarrow \nu_\beta \neq \bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta$$

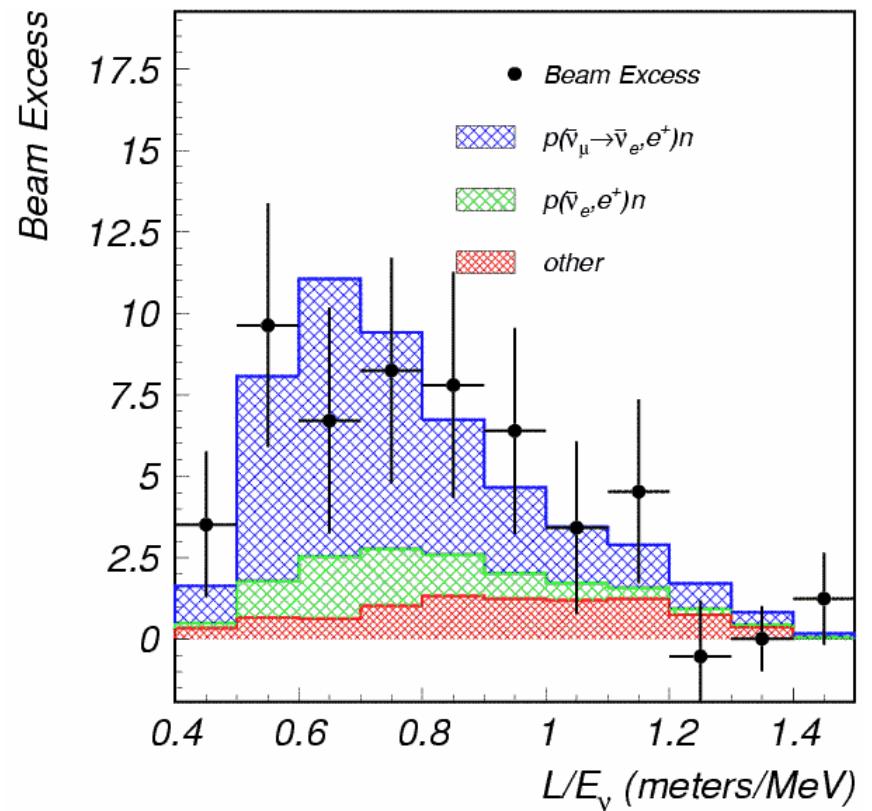
CP Violation

$$\nu_\alpha \rightarrow \nu_\beta \neq \bar{\nu}_\beta \rightarrow \bar{\nu}_\alpha$$

CPT Violation

LSND Signal

- LSND experiment
- Stopped pion beam
$$\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_\mu + \nu_e$$
- Excess of $\bar{\nu}_e$ in $\bar{\nu}_\mu$ beam
- $\bar{\nu}_e$ signature: Cherenkov light from e^+ with delayed γ from n-capture
- Excess = $87.9 \pm 22.4 \pm 6$ (3.8σ)

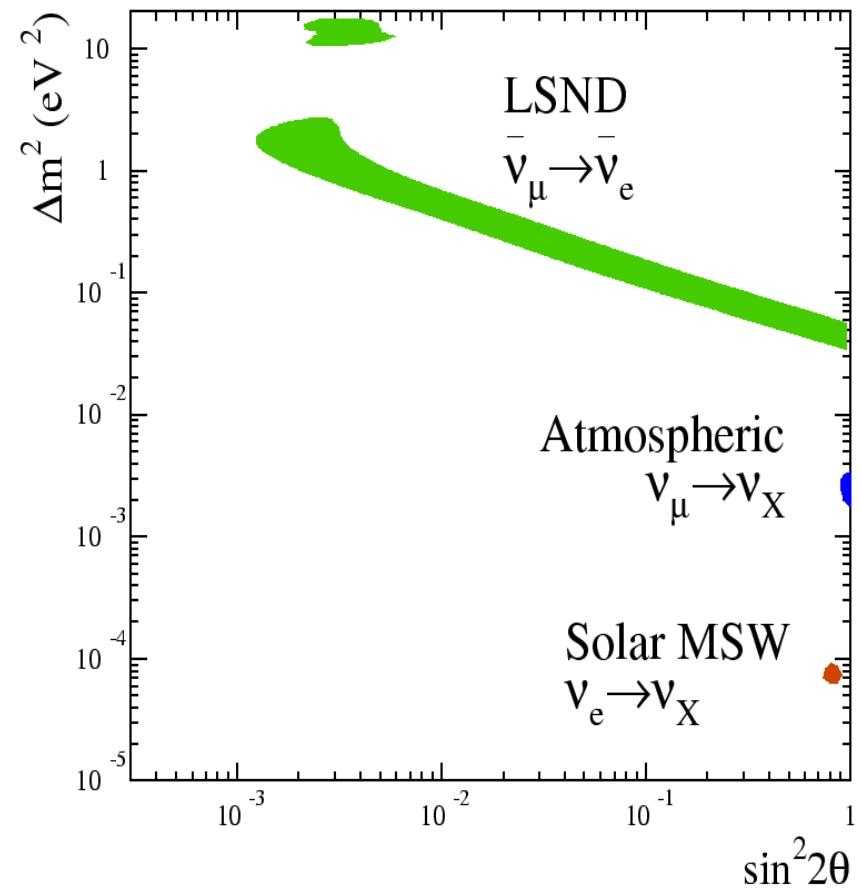
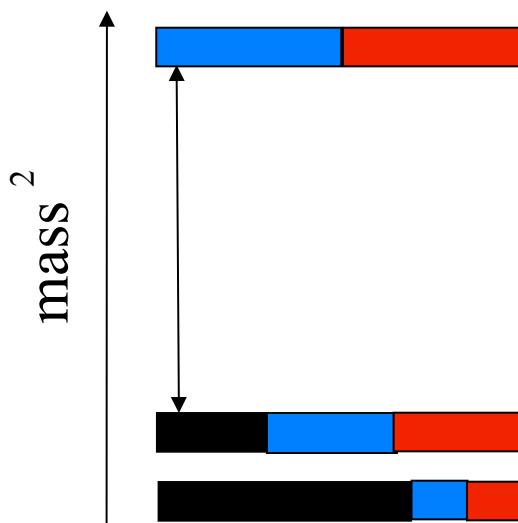


LSND Signal

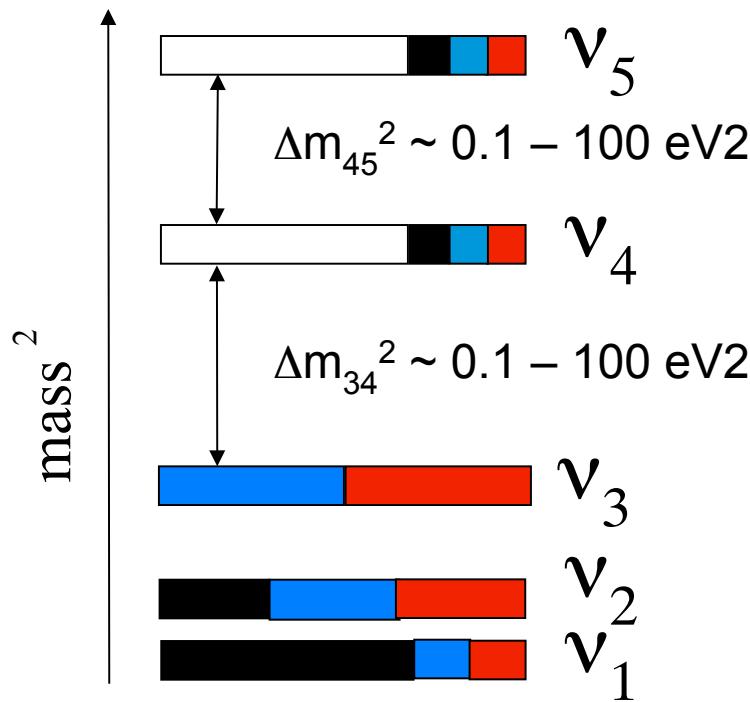
- Assuming two neutrino oscillations

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = \sin^2(2\theta) \sin^2\left(\frac{1.27 L \Delta m^2}{E}\right)$$
$$= 0.245 \pm 0.067 \pm 0.045 \%$$

- Can't reconcile LSND result with atmospheric and solar neutrino using only 3 Standard Model neutrinos – only two independent mass splittings

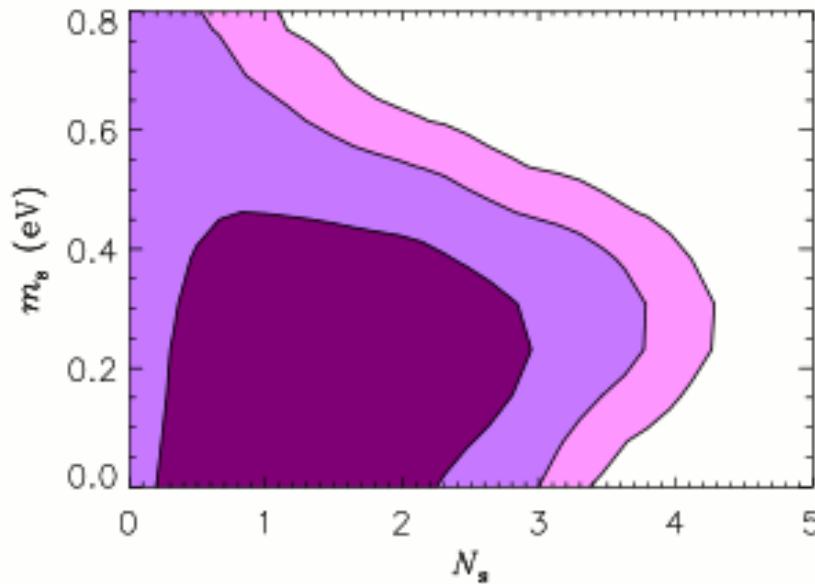


Sterile Neutrinos

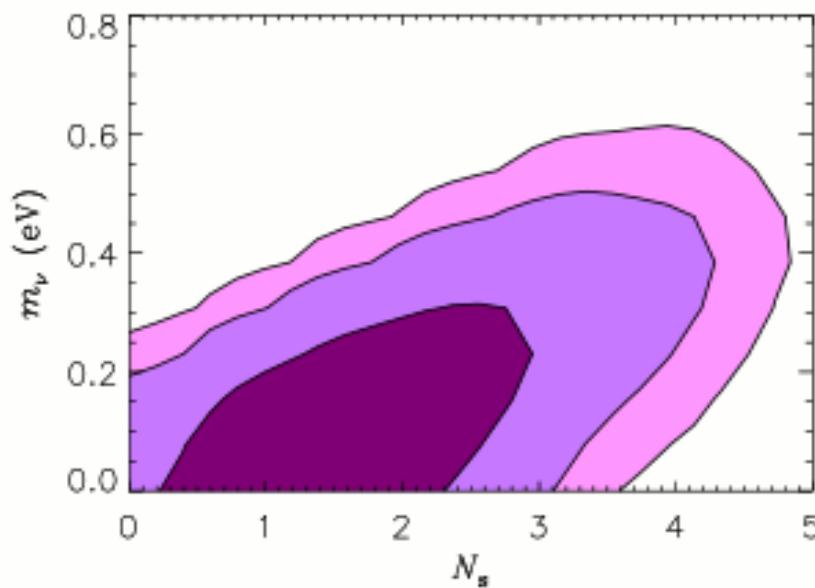


- 3+N models
- For N>1, model allows CP violation for short baseline
 - $\nu_\mu \rightarrow \nu_e \neq \bar{\nu}_\mu \rightarrow \bar{\nu}_e$

Cosmology Data Consistent with Extra Sterile Neutrinos (J. Hamann, et. al. arXiv:1006.5276)

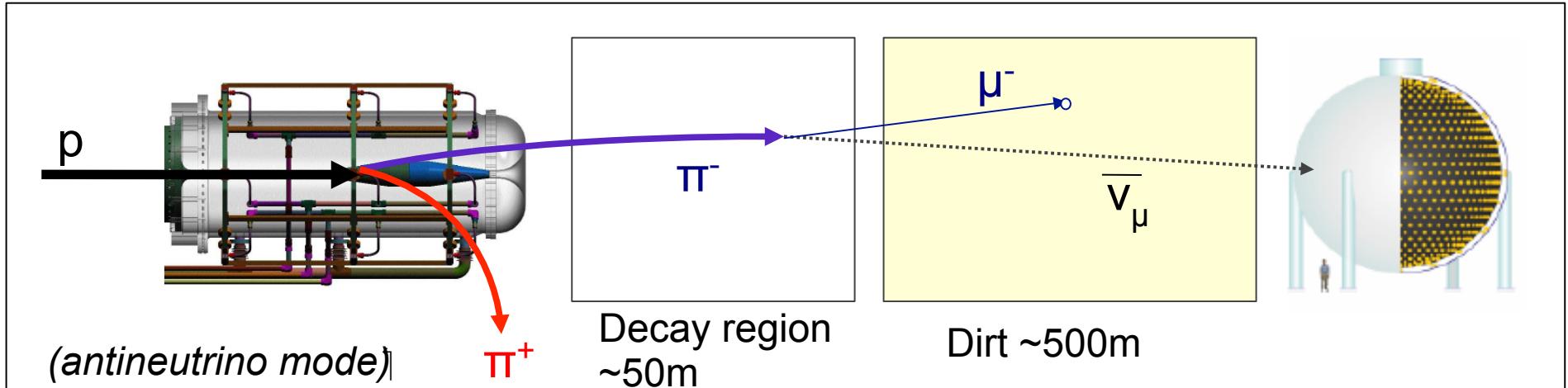


$$3 + N_s \\ m_\nu = 0$$



$$3 + N_s \\ m_s = 0$$

MiniBooNE Experiment



- Similar L/E as LSND
 - MiniBooNE $\sim 500\text{m}/\sim 500\text{MeV}$
 - LSND $\sim 30\text{m}/\sim 30\text{MeV}$
- Horn focused neutrino beam ($p+Be$)
 - Horn polarity \rightarrow neutrino or anti-neutrino mode
- 800t mineral oil Cherenkov detector

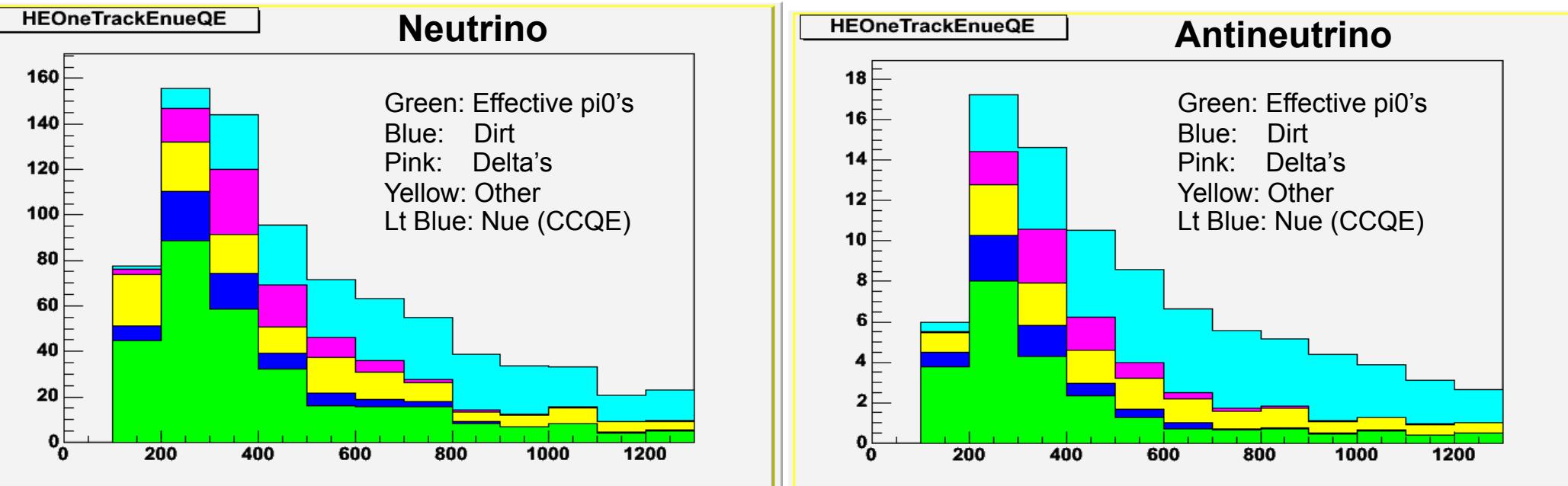
ν_e Event Rate Predictions

$$\# \text{Events} = \text{Flux} \times \text{Cross-sections} \times \text{Detector response}$$

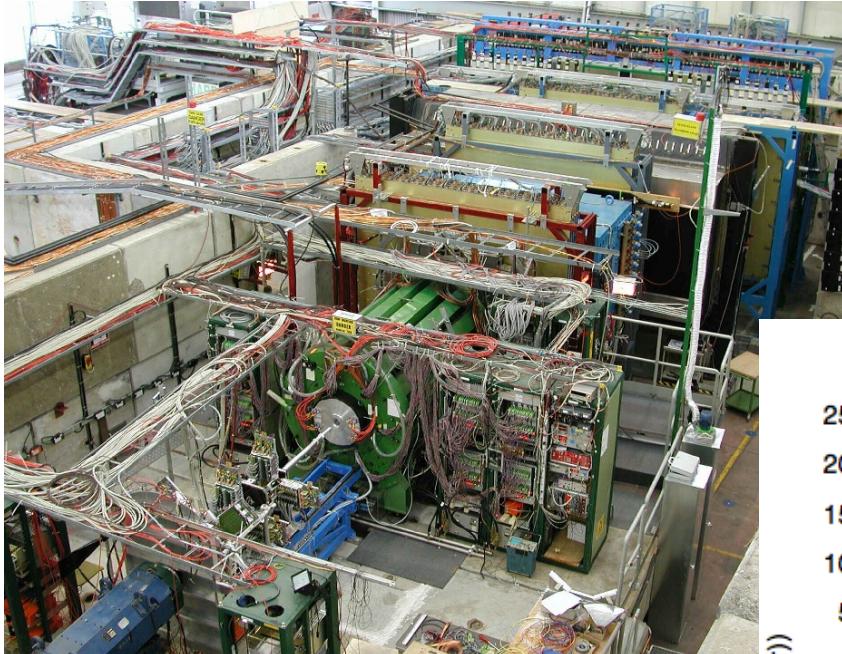
**External measurements
(HARP, etc)**
 ν_μ rate constrained by neutrino data

External and MiniBooNE measurements
- π^0 , delta and dirt backgrounds constrained from data.

Detailed detector simulations checked with neutrino data and calibration sources.



Modeling Production of Secondary Pions

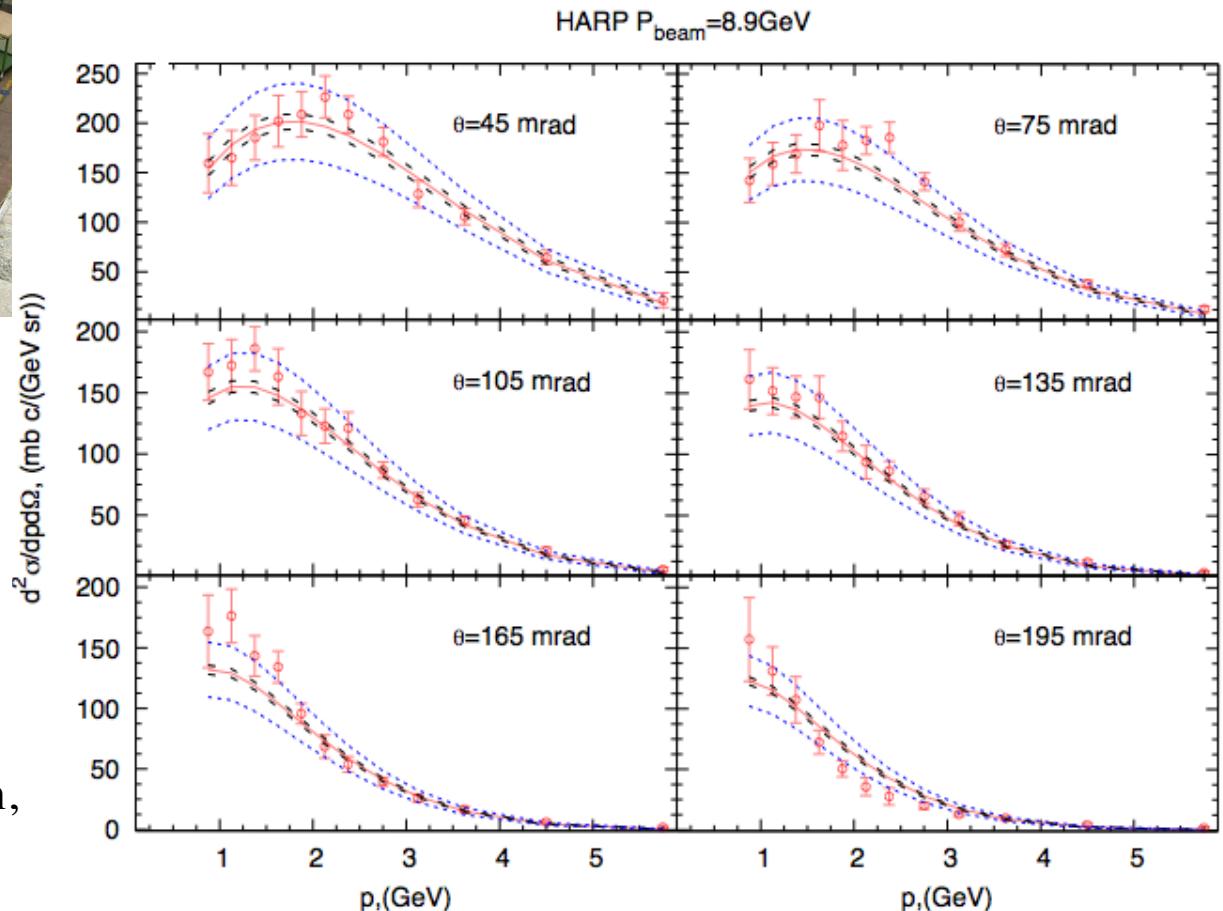


Data are fit to
a Sanford-Wang
parameterization.

HARP collaboration,
hep-ex/0702024

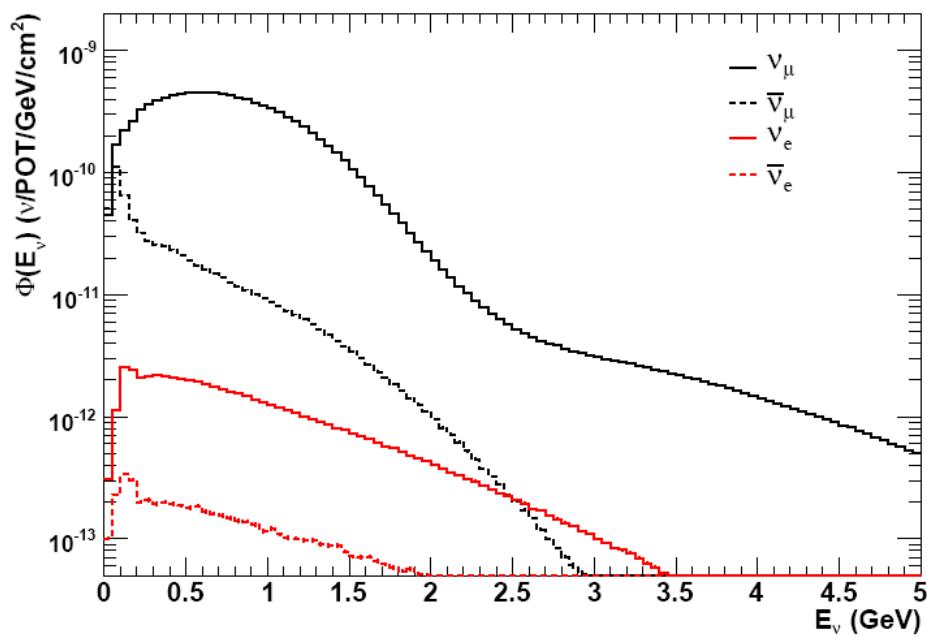
- HARP (CERN)

- 5% λ Beryllium target
- 8.9 GeV proton beam momentum
- π^+ & π^-

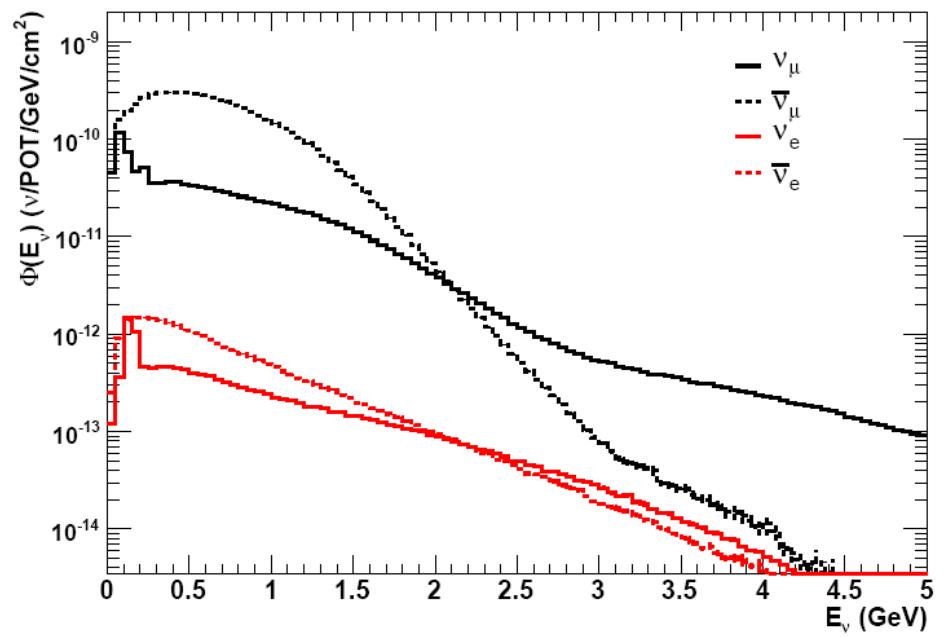


Neutrino Flux from GEANT4 Simulation

Neutrino-Mode Flux

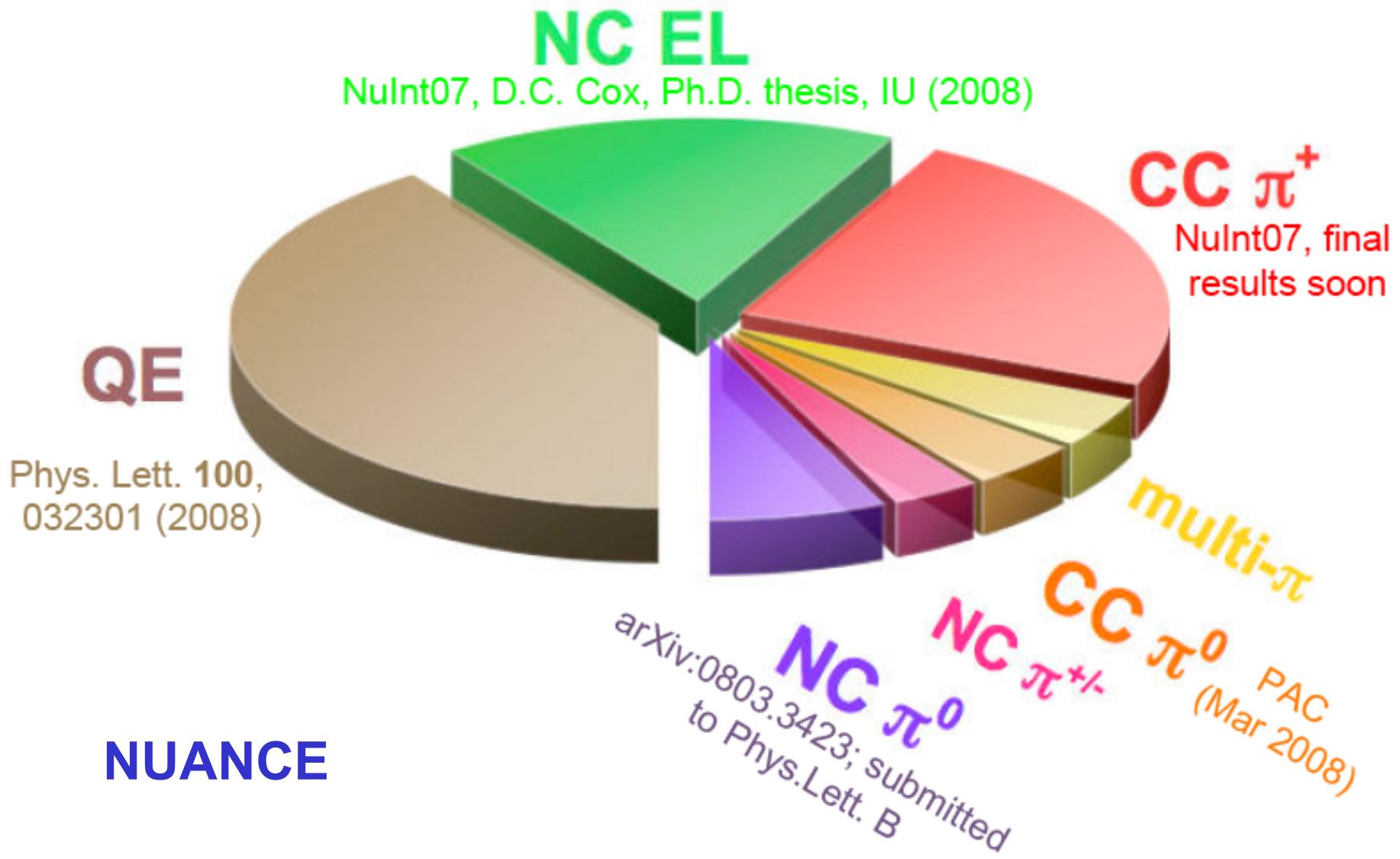


Antineutrino-Mode Flux

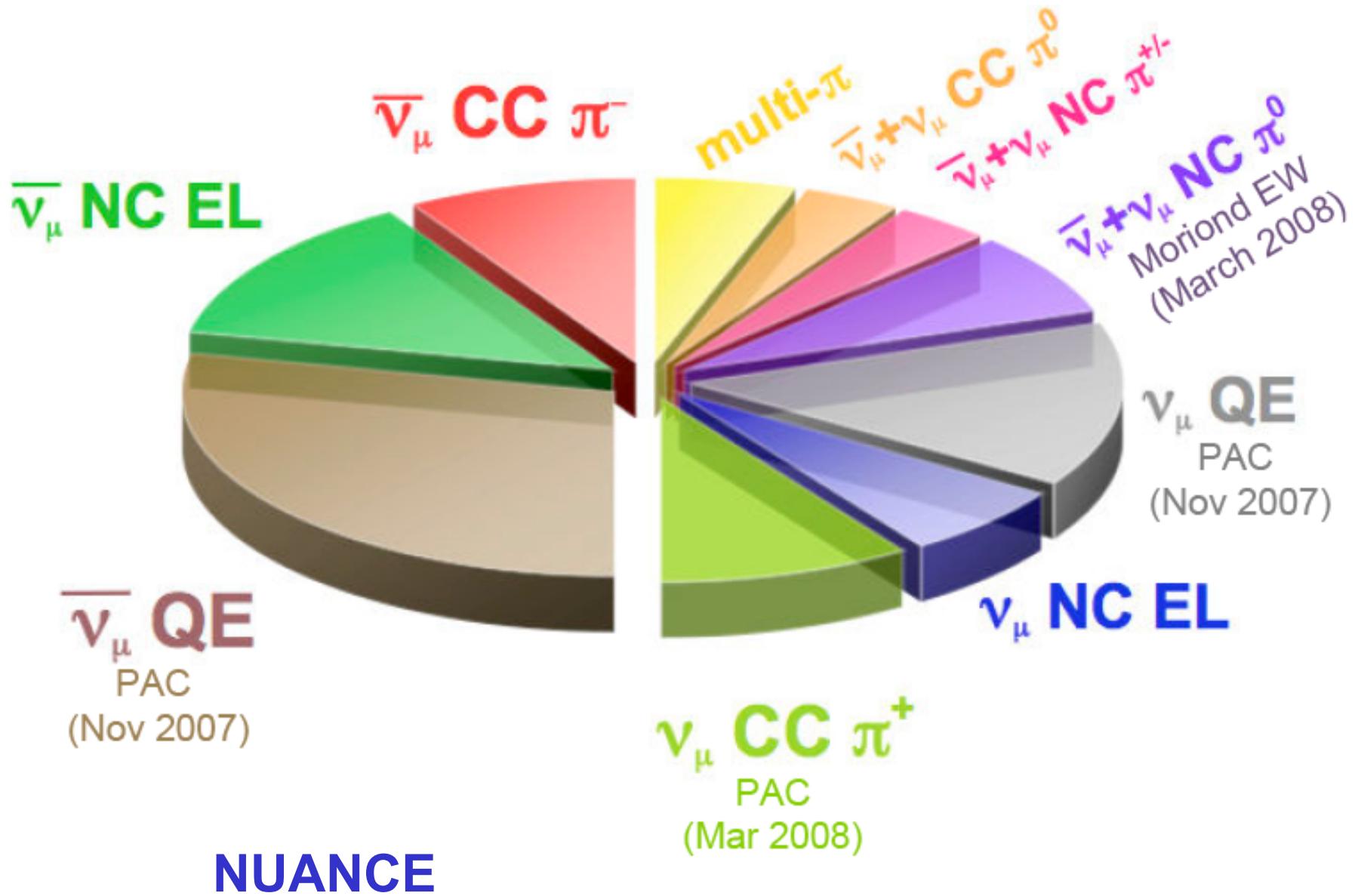


Wrong-sign background is ~6% for Nu-Mode & ~18% for Antinu-Mode
Intrinsic ν_e background is ~0.5% for both Nu-Mode & Antinu-Mode

Neutrino Cross Sections

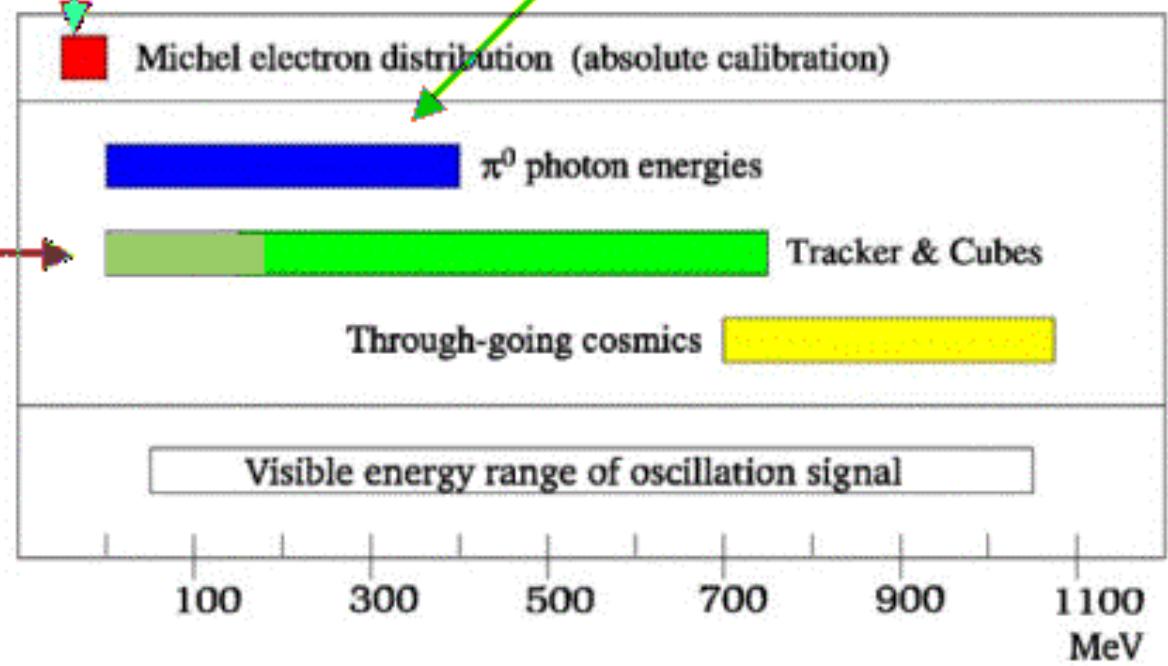
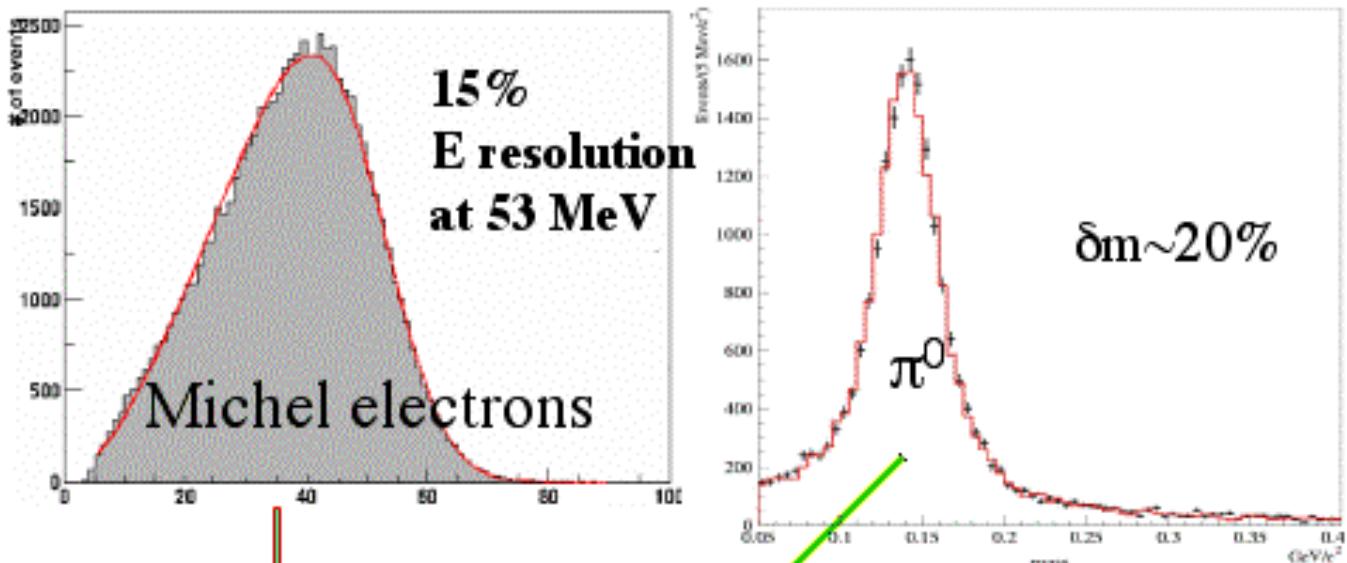
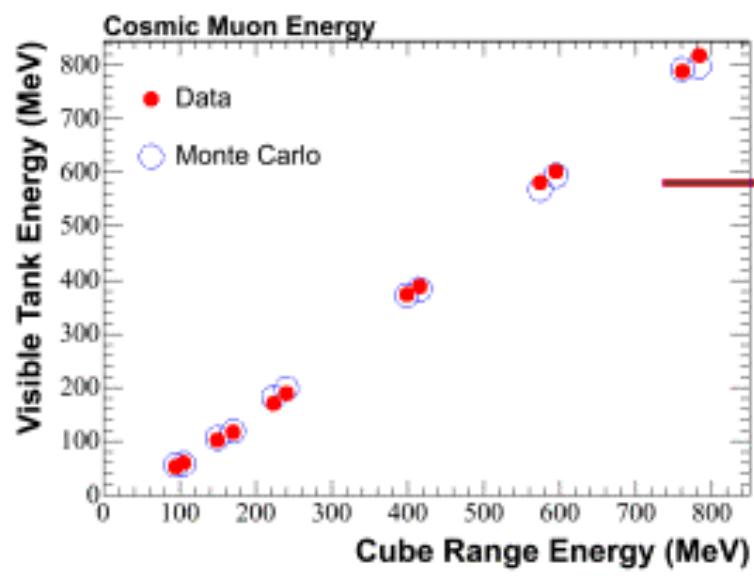
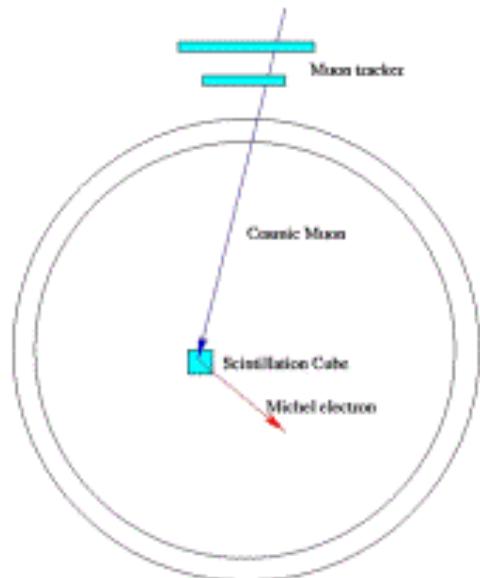


Antineutrino Cross Sections



Calibration Sources

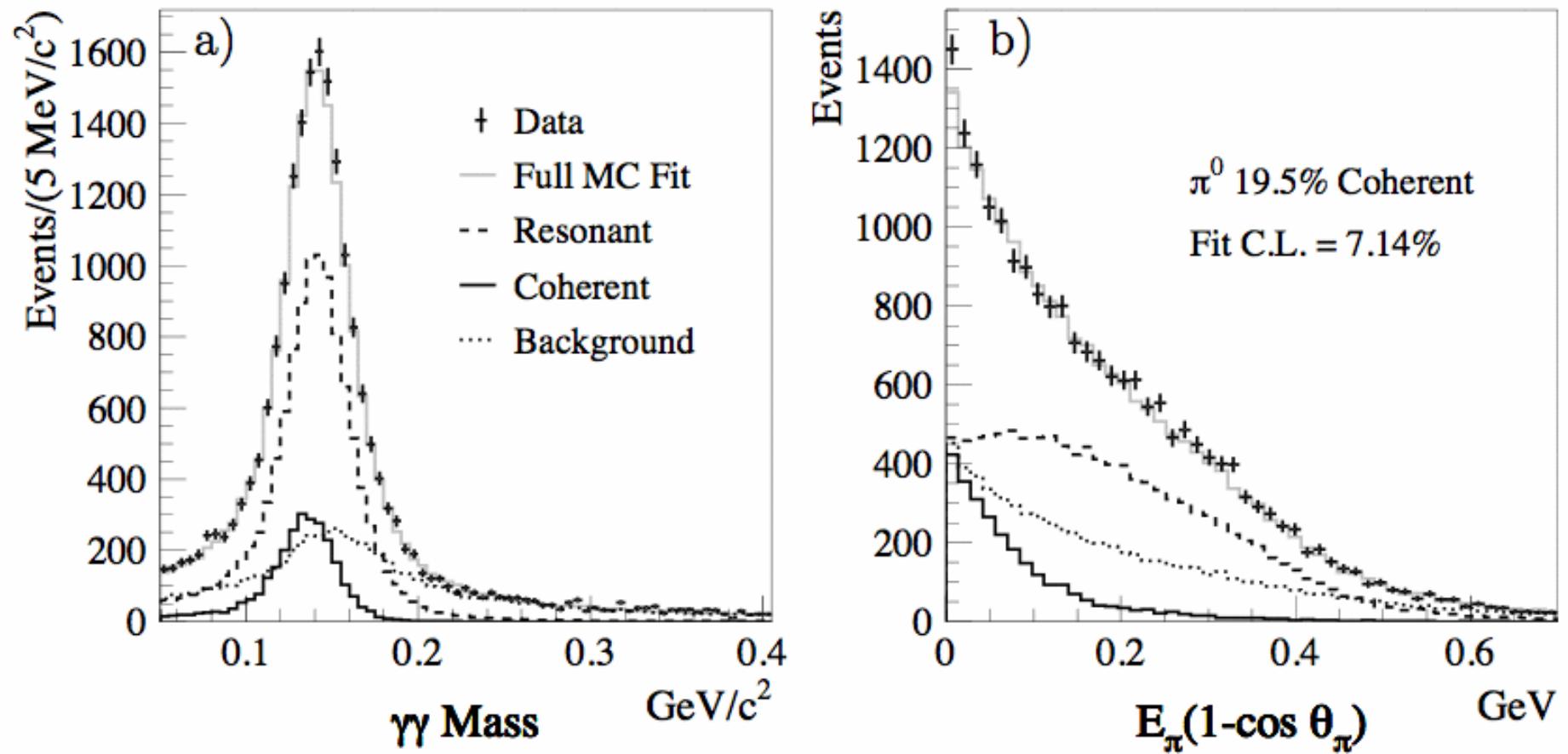
Tracker system



NC π^0 Scattering

A. A. Aguilar-Arevalo et al., Phys. Lett. B 664, 41 (2008)

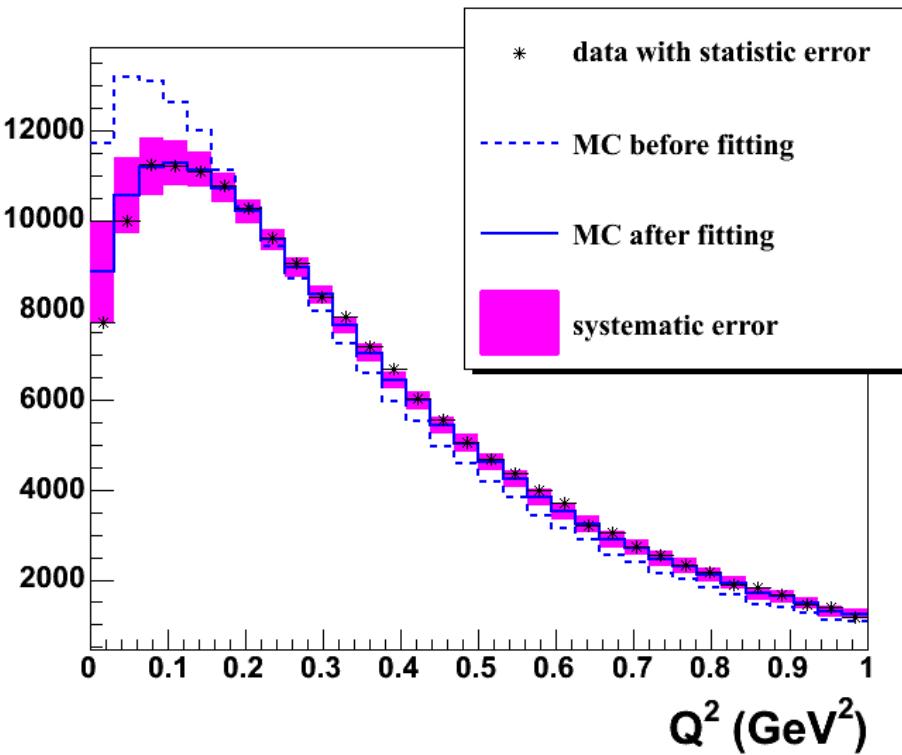
coherent fraction=19.5+-1.1+-2.5%



ν_μ CCQE Scattering

A. A. Aguilar-Arevalo et al., Phys. Rev. Lett. 100, 032301 (2008)

186000 muon neutrino events



Fermi Gas Model describes CCQE

ν_μ data well

$M_A = 1.23 \pm 0.20$ GeV

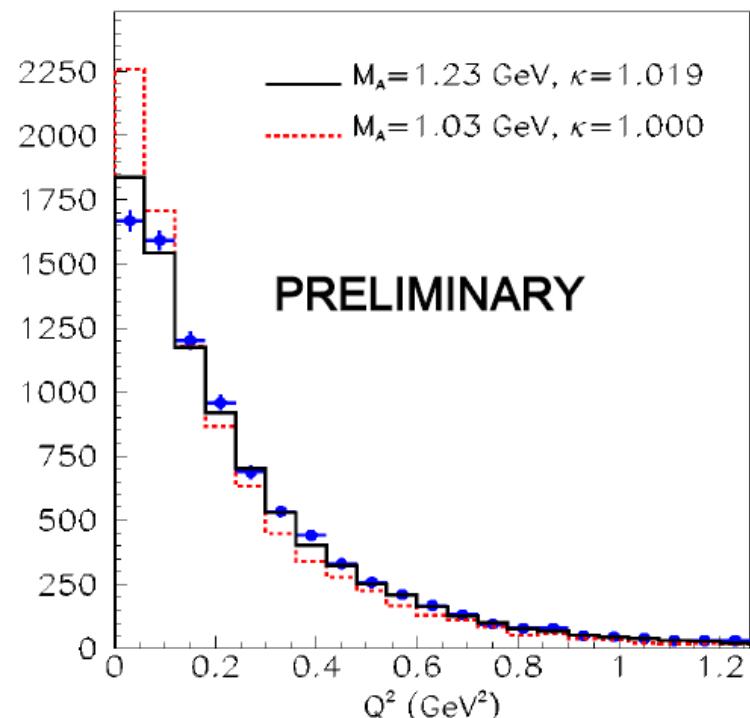
$\kappa = 1.019 \pm 0.011$

Also used to model ν_e and $\bar{\nu}_e$ interactions

From Q^2 fits to MB ν_μ CCQE data:
 M_A^{eff} -- effective axial mass
 κ -- Pauli Blocking parameter

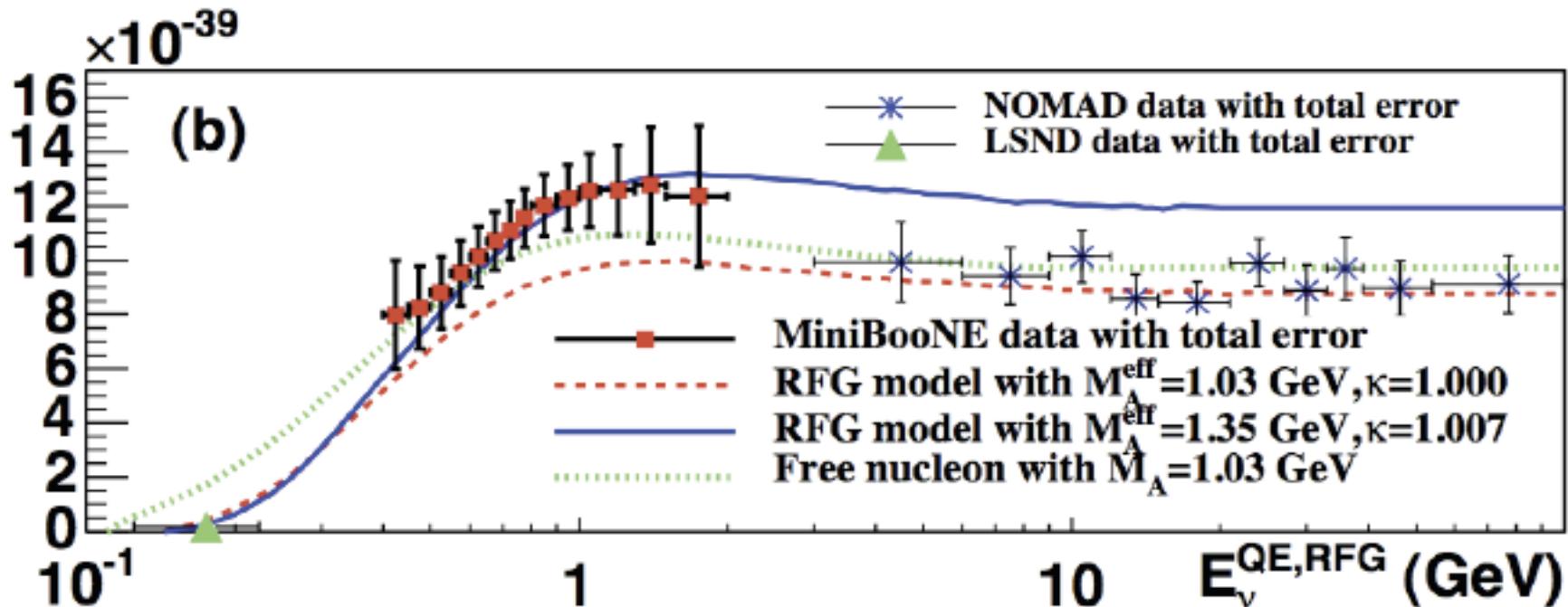
From electron scattering data:
 E_b -- binding energy
 p_f -- Fermi momentum

14000 anti-muon neutrinos



ν_μ CCQE Scattering

A.A. Aguilar-Arevalo, Phys. Rev. D81, 092005 (2010).



Extremely surprising result - CCQE $\sigma_{\nu\mu}(^{12}\text{C}) > 6 \sigma_{\nu\mu}(\text{n})$

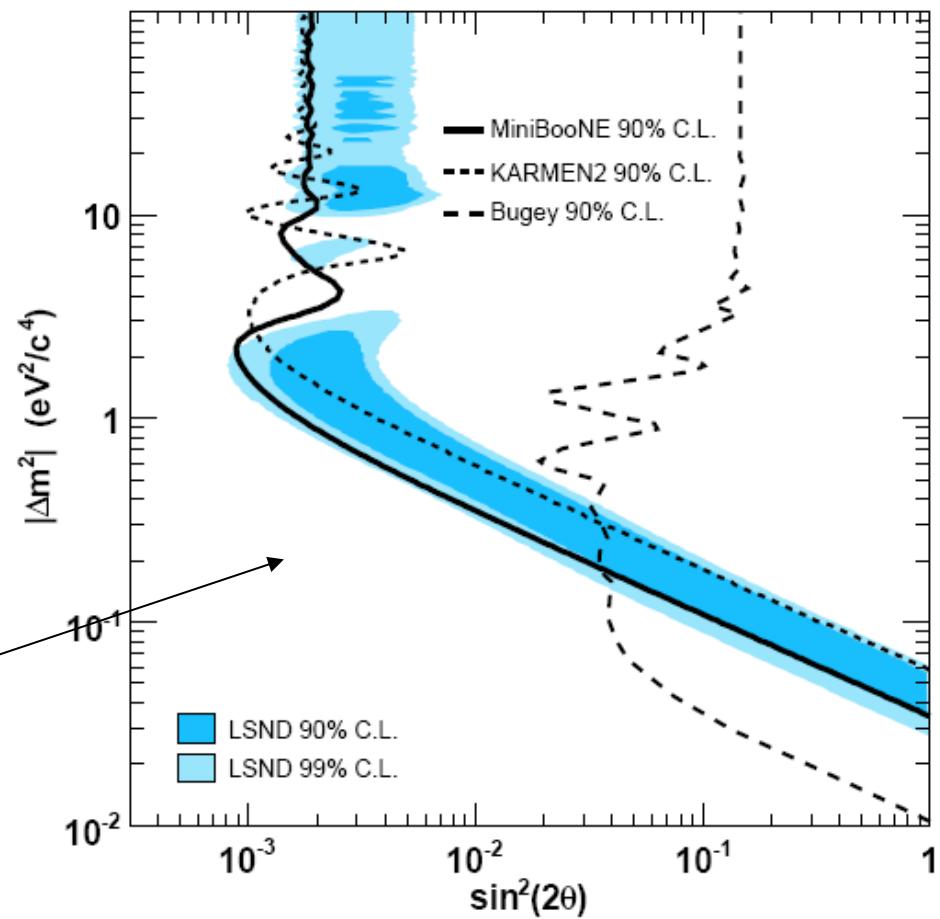
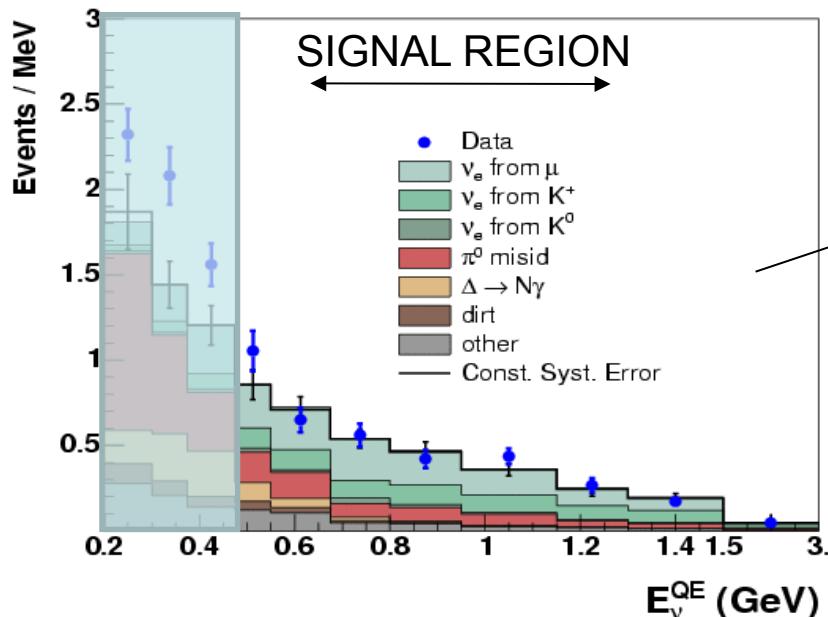
How can this be? Not seen before, requires correlations. Fermi Gas has no correlations and should be an overestimate.

A possible explanation involves short-range correlations & 2-body pion-exchange currents: Joe Carlson et al., Phys. Rev. C65, 024002 (2002) & Gerry Garvey.

MiniBooNE Neutrino Oscillation Results

A.A. Aguilar-Arevalo et al., PRL 102, 101802 (2009)

- 6.5e20 POT
- No excess of events in signal region ($E>475$ MeV)
- Ruled out simple 2ν oscillations as LSND explanation (assuming no CP or CPT violation)



Phys. Rev. Lett. 98, 231801 (2007)

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MiniBooNE Neutrino Oscillation Results

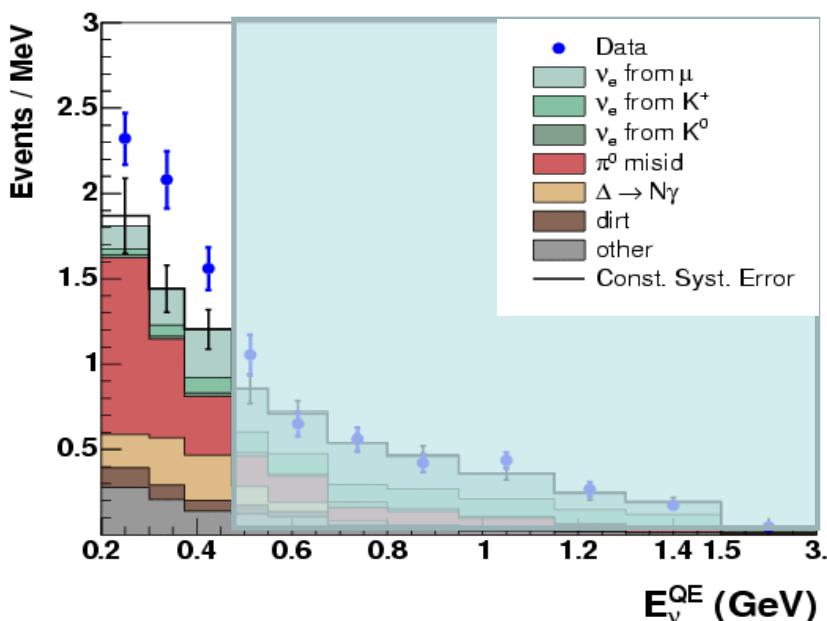
A.A. Aguilar-Arevalo et al., PRL 102, 101802 (2009)

Excess of events observed at low energy:

$$128.8 \pm 20.4 \pm 38.3 \text{ (3.0}\sigma\text{)}$$

Shape not consistent with simple 2ν oscillations

Magnitude consistent with LSND



Anomaly Mediated Neutrino-Photon Interactions at Finite Baryon Density: Jeffrey A. Harvey, Christopher T. Hill, & Richard J. Hill, arXiv:0708.1281

CP-Violation 3+2 Model: Maltoni & Schwetz, arXiv:0705.0107; T. Goldman, G. J. Stephenson Jr., B. H. J. McKellar, Phys. Rev. D75 (2007) 091301.

Extra Dimensions 3+1 Model: Pas, Pakvasa, & Weiler, Phys. Rev. D72 (2005) 095017

Lorentz Violation: Katori, Kostelecky, & Tayloe, Phys. Rev. D74 (2006) 105009

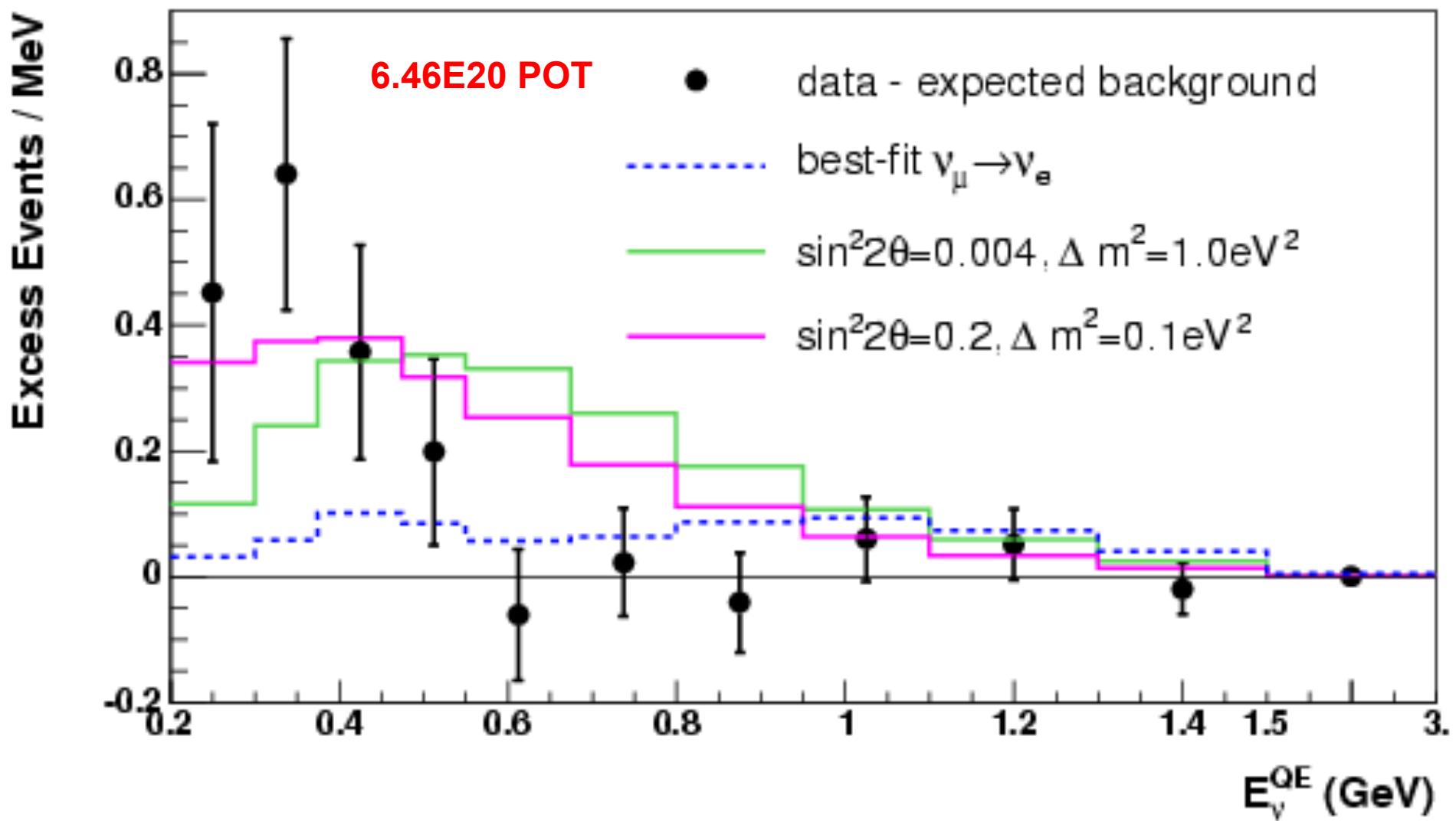
CPT Violation 3+1 Model: Barger, Marfatia, & Whisnant, Phys. Lett. B576 (2003) 303

New Gauge Boson with Sterile Neutrinos: Ann E. Nelson & Jonathan Walsh, arXiv:0711.1363

MiniBooNE Data Show a Low-Energy Excess

A.A. Aguilar-Arevalo et al., PRL 102, 101802 (2009)

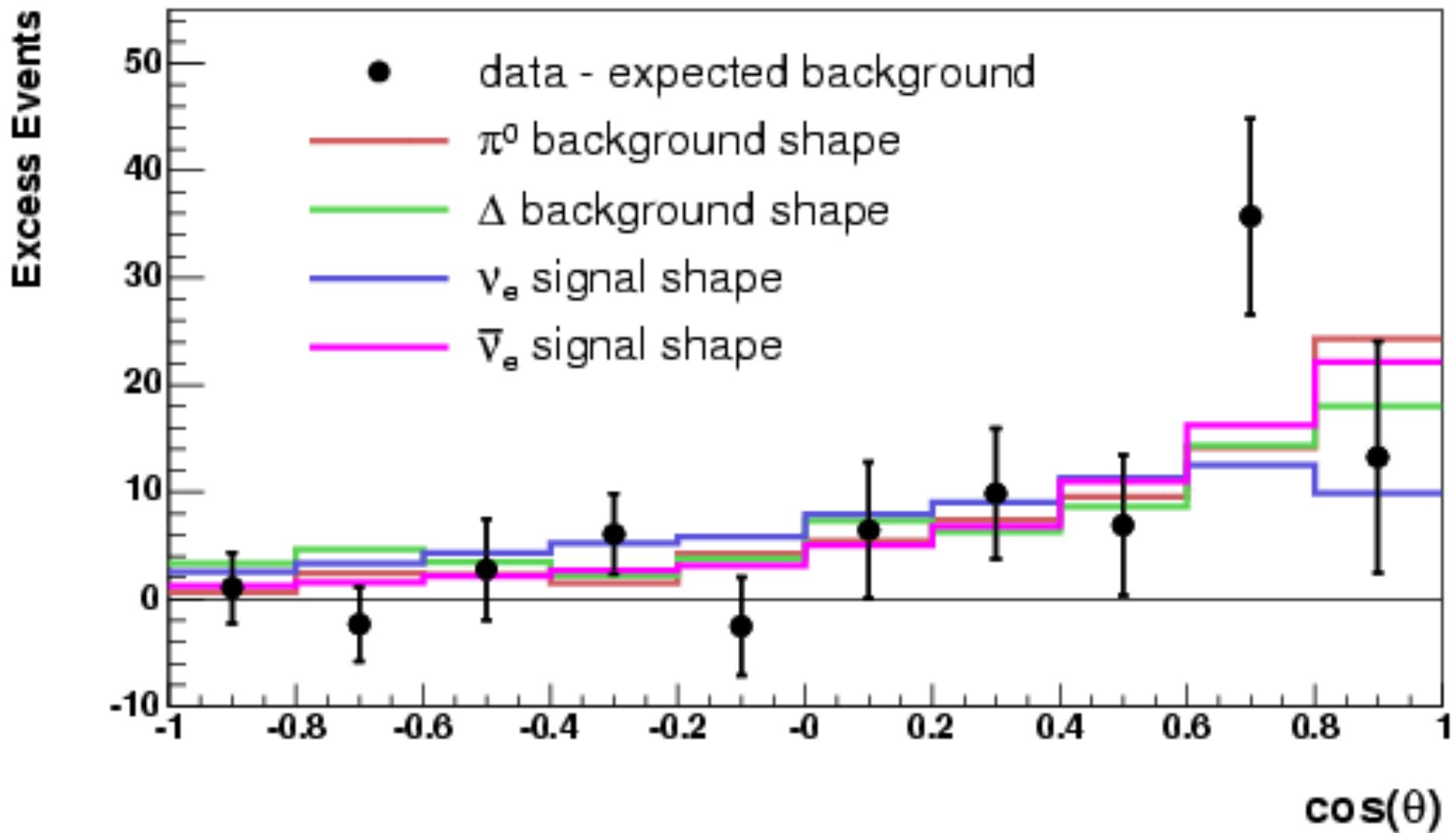
Excess from 200-475 MeV = $128.8 \pm 20.4 \pm 38.3$ events



Number of Excess Events

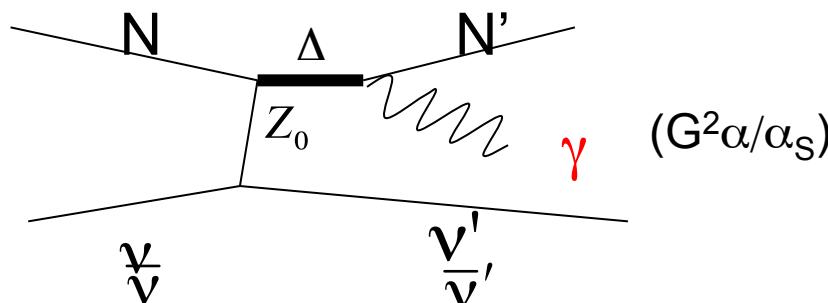
Energy (MeV)	Data	Background	Excess	# σ_{tot}	(# σ_{stat})
200-300	232	186.8+-26.0	45.2+-13.7+-22.1	1.7	(3.3)
300-475	312	228.3+-24.5	83.7+-15.1+-19.3	3.4	(5.5)
200-475	544	415.2+-43.4	128.8+-20.4+-38.3	3.0	(6.3)
475-1250	408	385.9+-35.7	22.1+-19.6+-29.8	0.6	(1.1)
200-1250	952	801.0+-58.1	151.0+-28.3+-50.7	2.6	(5.3)

Low-Energy Excess vs $\cos\theta$

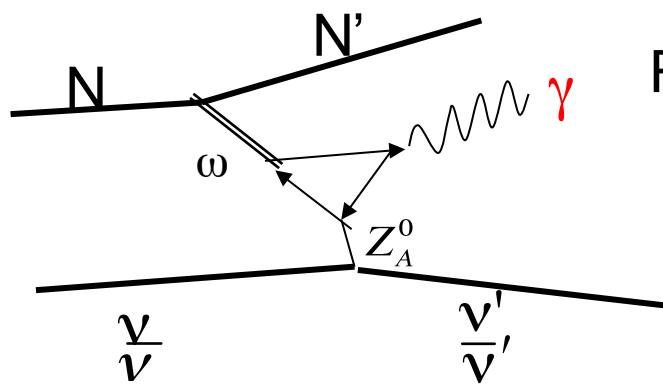


Backgrounds: Order ($G^2\alpha\alpha_s$) , single γ FS?

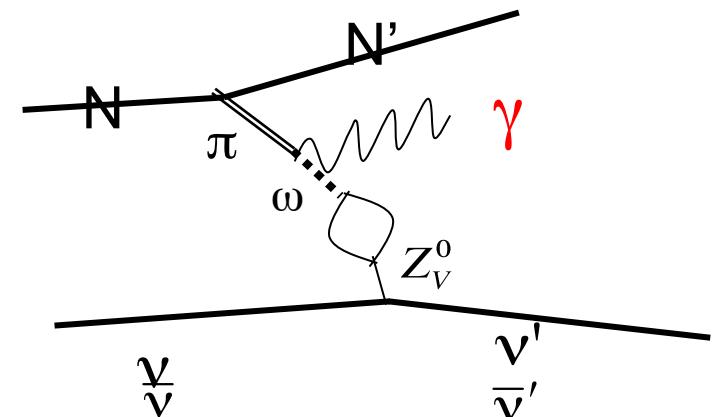
Dominant process accounted for in MC!



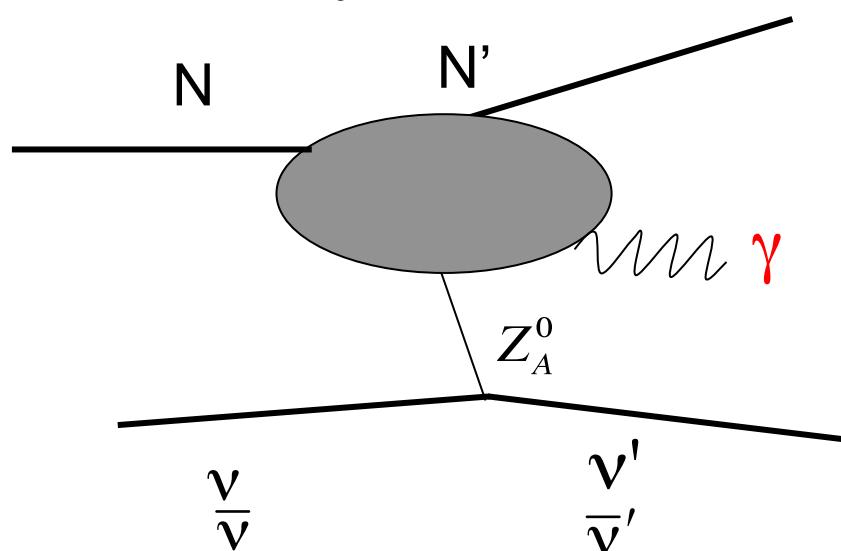
Radiative Delta Decay



Axial Anomaly



Other PCAC

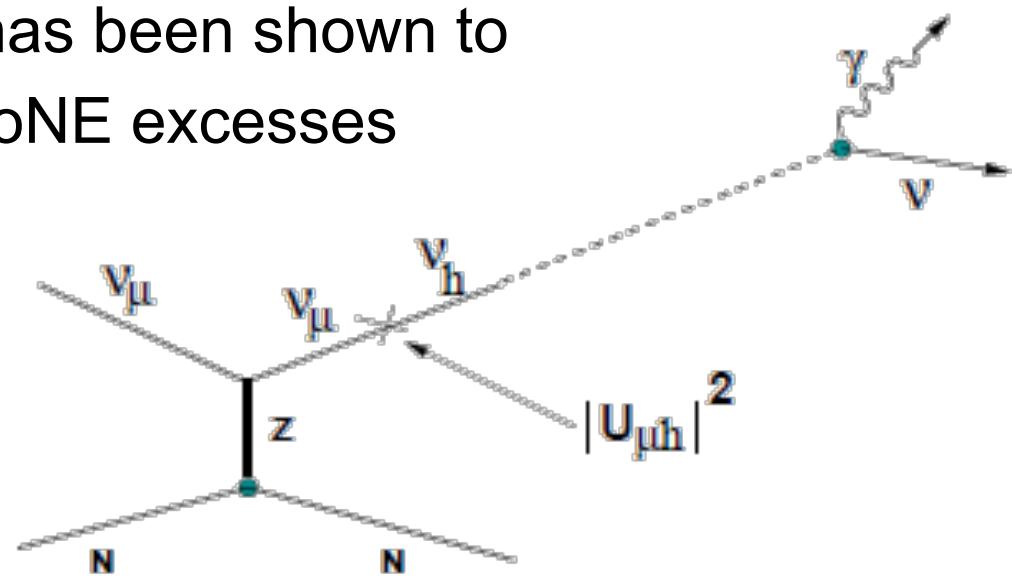
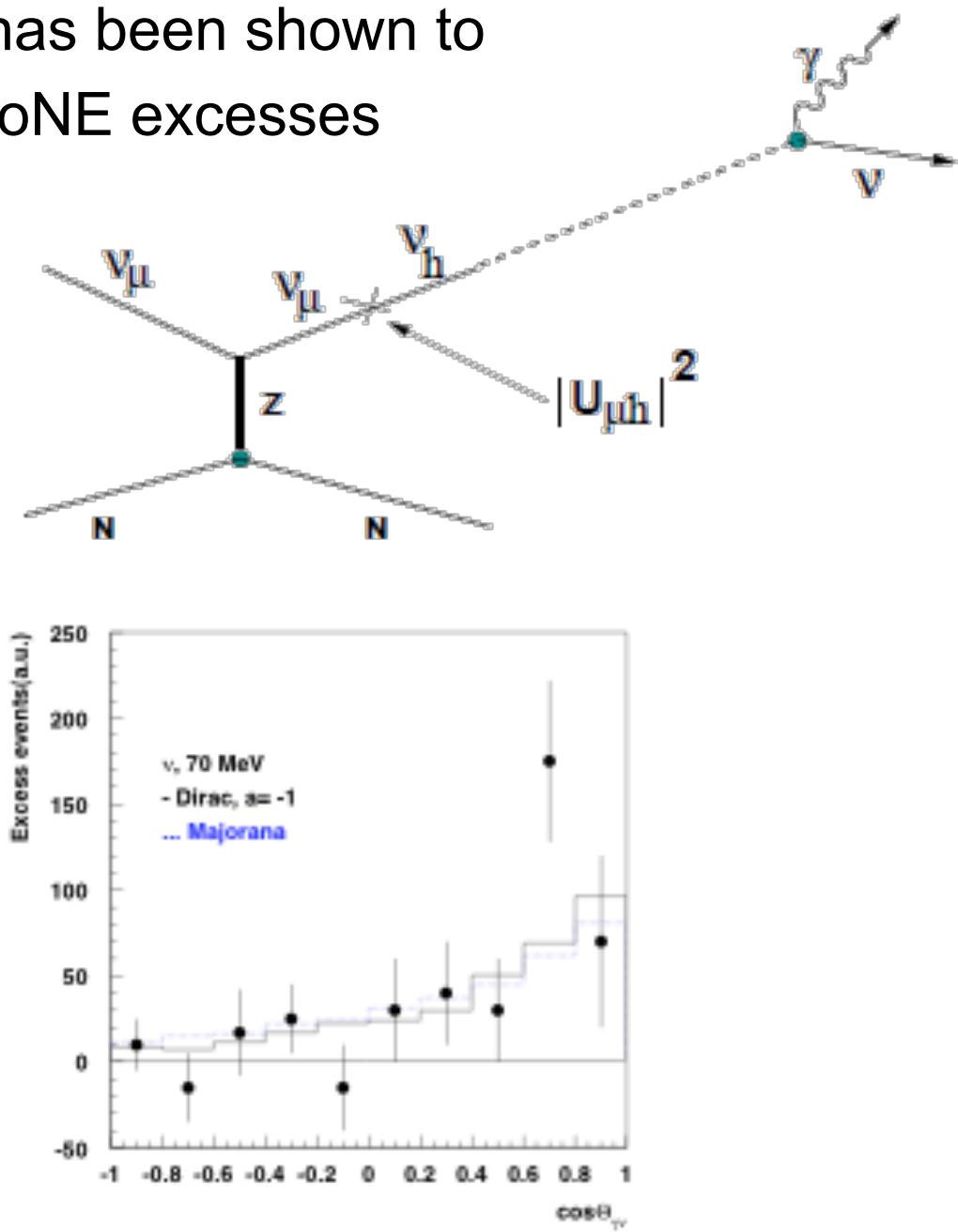
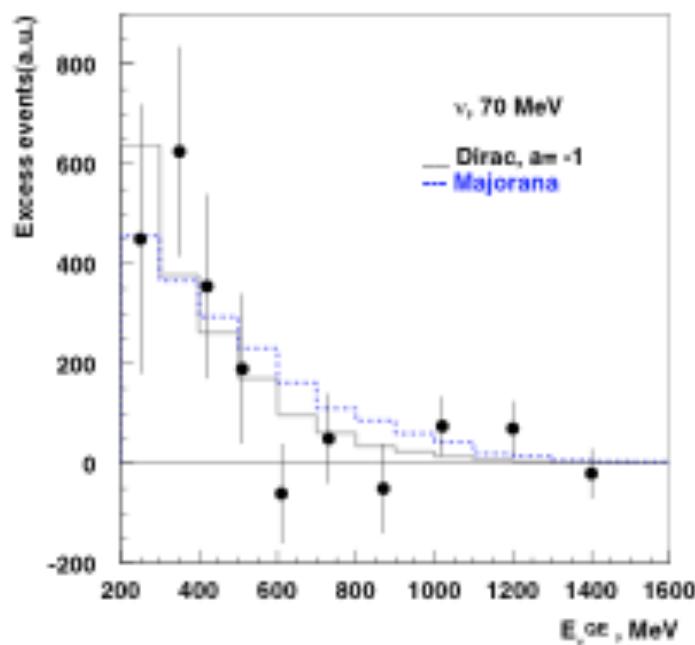


*So far no one has found a NC process to account for the $\nu/\bar{\nu}$ difference & the ν low-energy excess. Work is in progress:
R. Hill, arXiv:0905.0291
Jenkins & Goldman, arXiv:0906.0984
Serot & Zhang, arXiv:1011.5913*

Sterile ν Decay?

- The decay of a ~ 50 MeV sterile ν has been shown to accommodate the LSND & MiniBooNE excesses
 - Gninenko, PRL 103, 241802 (2009)

arXiv:1009.5536



Lorentz Violation?

A simple Lorentz-violating texture for neutrino mixing

Jorge S. Díaz and V. Alan Kostelecký

Physics Department, Indiana University, Bloomington, IN 47405, U.S.A.

(Dated: IUHET 552, December 2010)

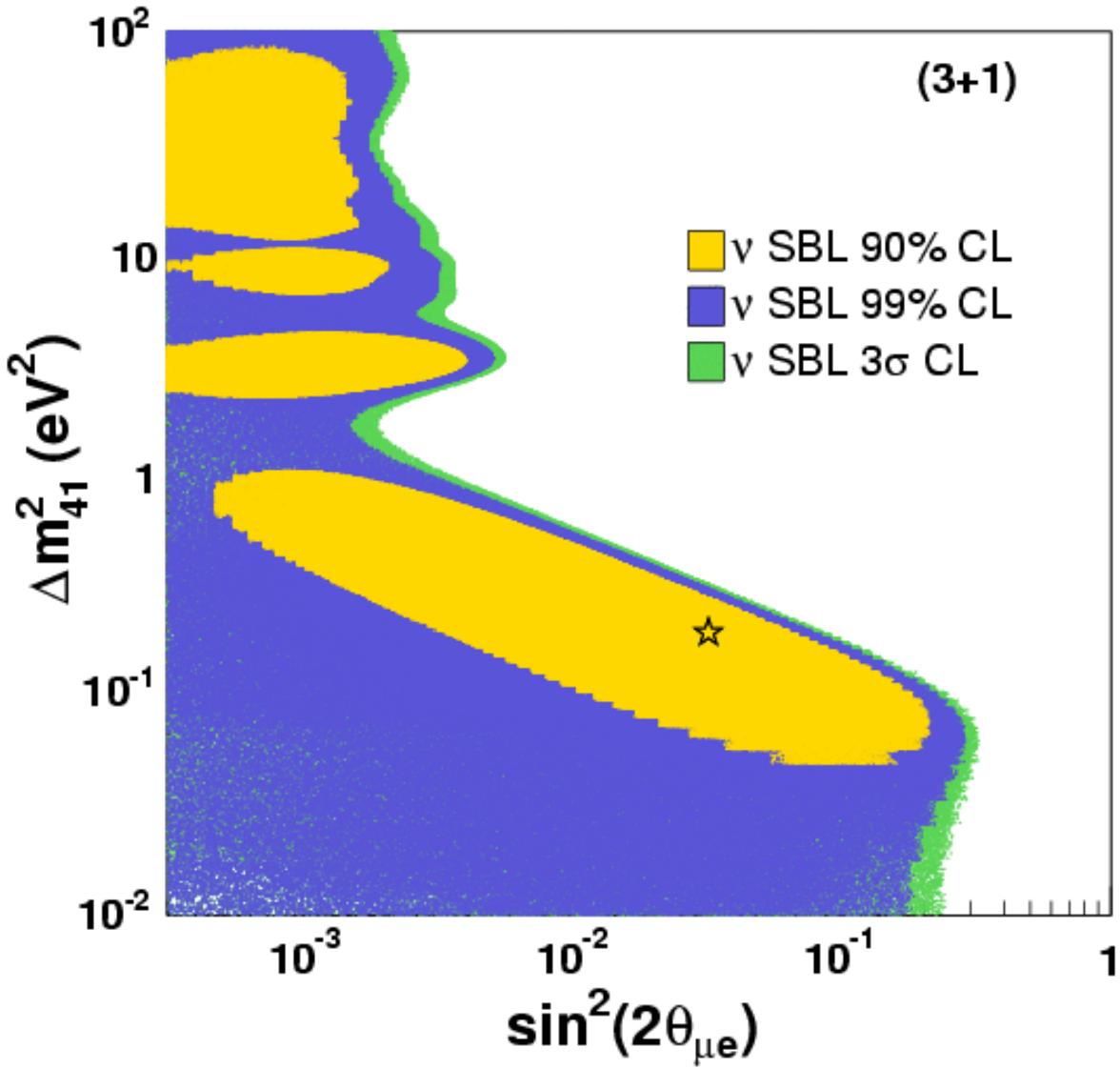
Abstract

A three-parameter model of neutrino oscillations based on a simple Lorentz- and CPT-violating texture is presented. The model is consistent with established data and naturally generates low-energy and neutrino-antineutrino anomalies of the MiniBooNE type. Texture enhancements accommodate the LSND signal and the MINOS anomaly.

arxiv: 1012.5985

More Complicated ν Oscillations?

3+1 Global Fit to World Neutrino Data Only



G. Karagiorgi et al.,
arXiv:0906.1997

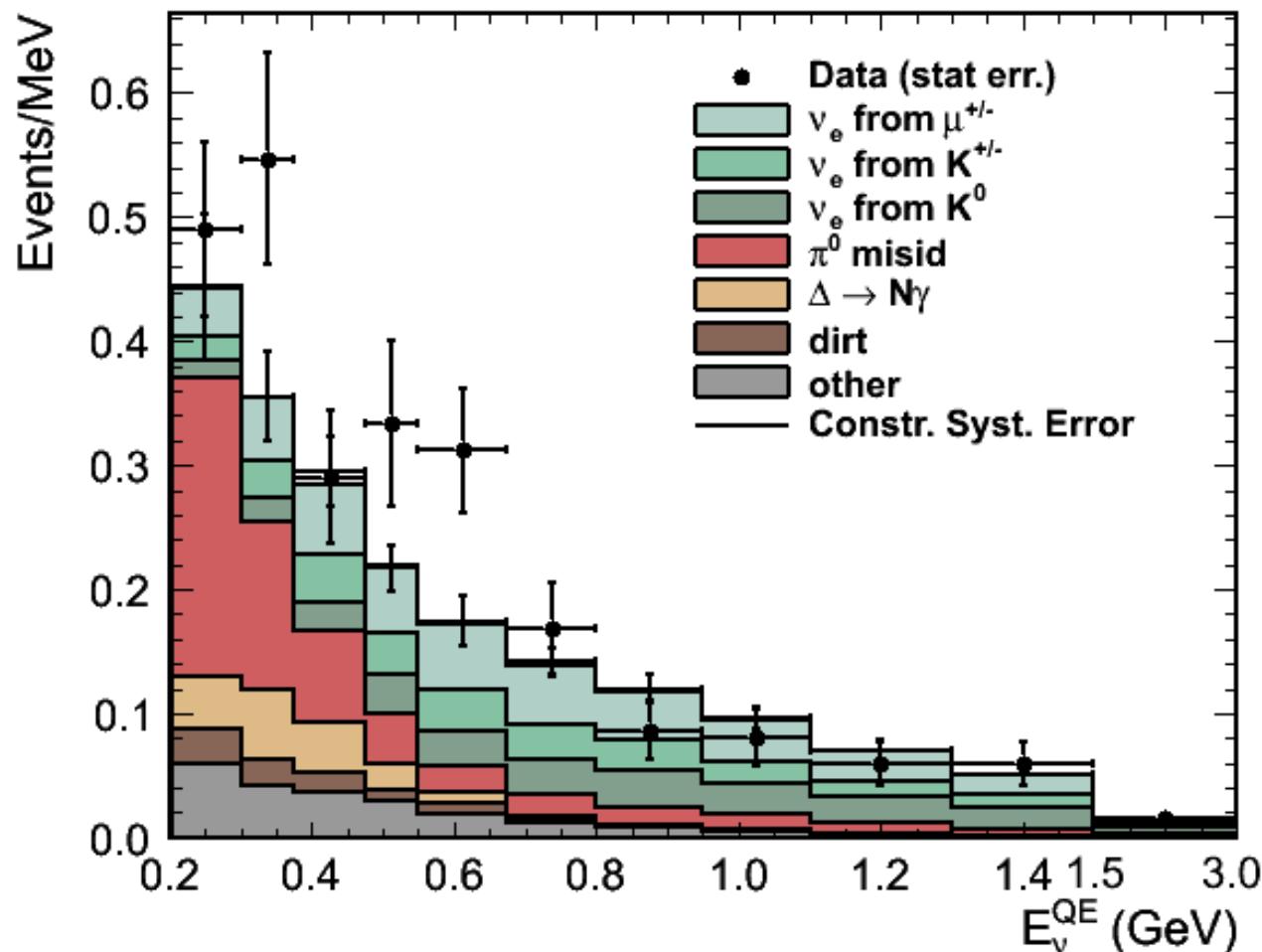
Best 3+1 Fit:
 $\Delta m_{41}^2 = 0.19 \text{ eV}^2$
 $\sin^2 2\theta_{\mu e} = 0.031$
 $\chi^2 = 90.5/90 \text{ DOF}$
Prob. = 46%

Predicts ν_μ & ν_e disappearance of $\sin^2 2\theta_{\mu\mu} \sim 3.1\%$ and $\sin^2 2\theta_{ee} \sim 3.4\%$

MiniBooNE Antineutrino Oscillation Results

A. A. Aguilar-Arevalo, Phys. Rev. Lett. 105, 181801 (2010)

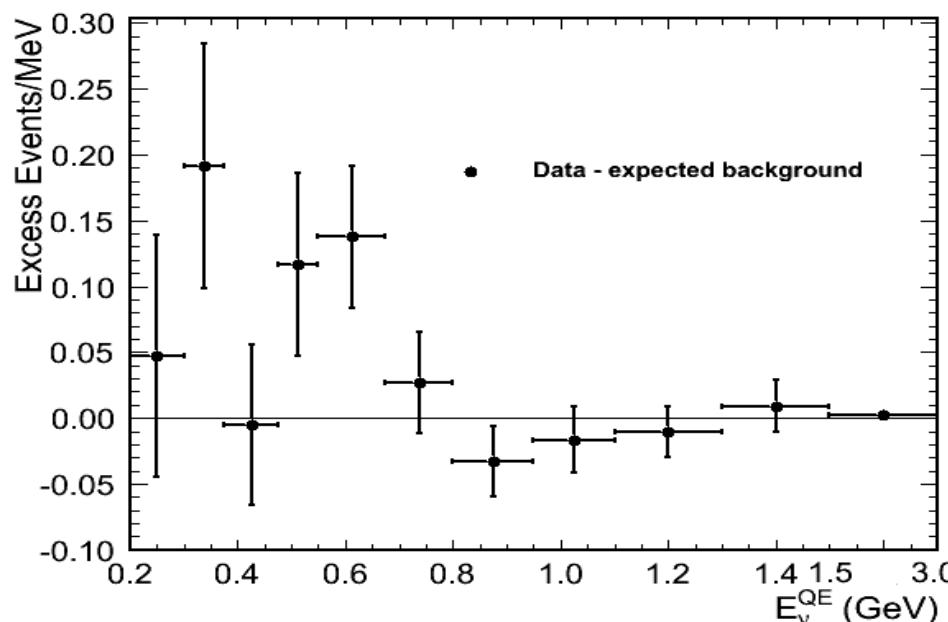
- 5.66e20 POT



MiniBooNE Antineutrino Null Probability

- Absolute χ^2 probability of null point (background only) - model independent
- Frequentist approach

475-1250 MeV	chi2/NDF	probability
$\nu_\mu \rightarrow \nu_e$	6.1/6	40%
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	18.5/6	0.5%

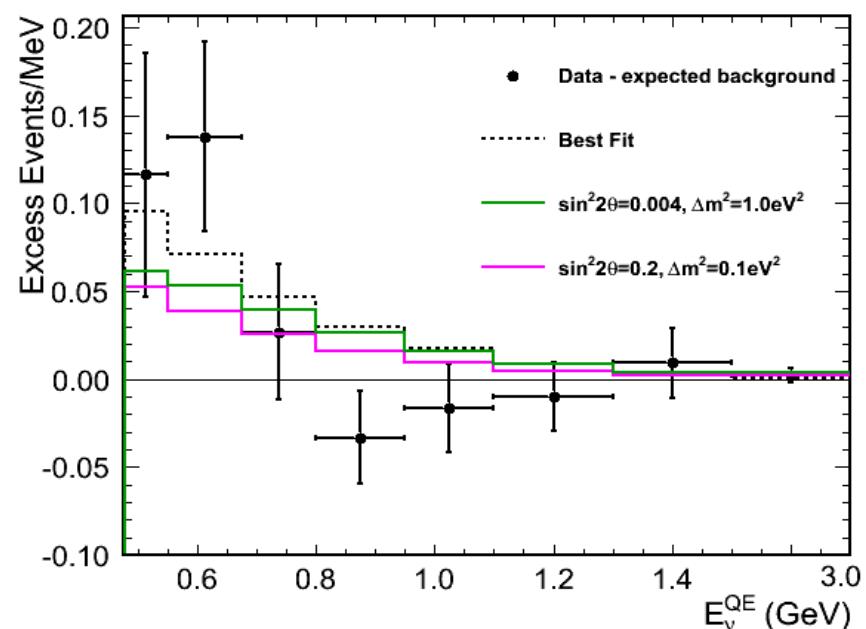
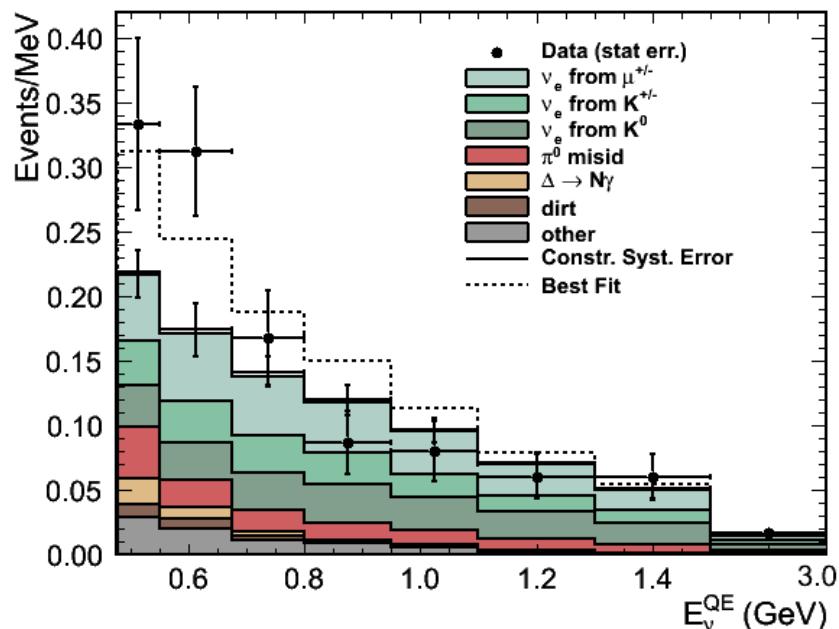
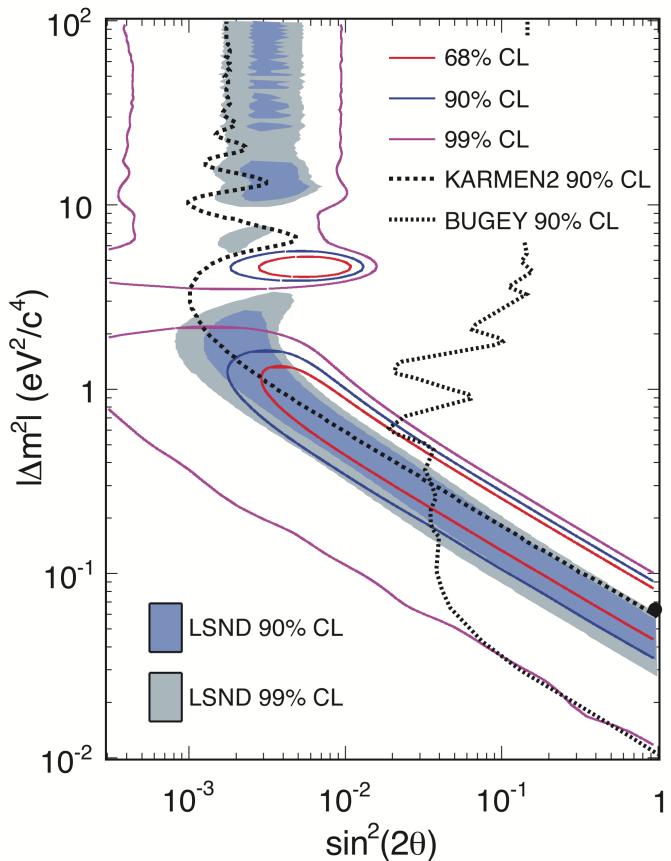


Number of Excess Events

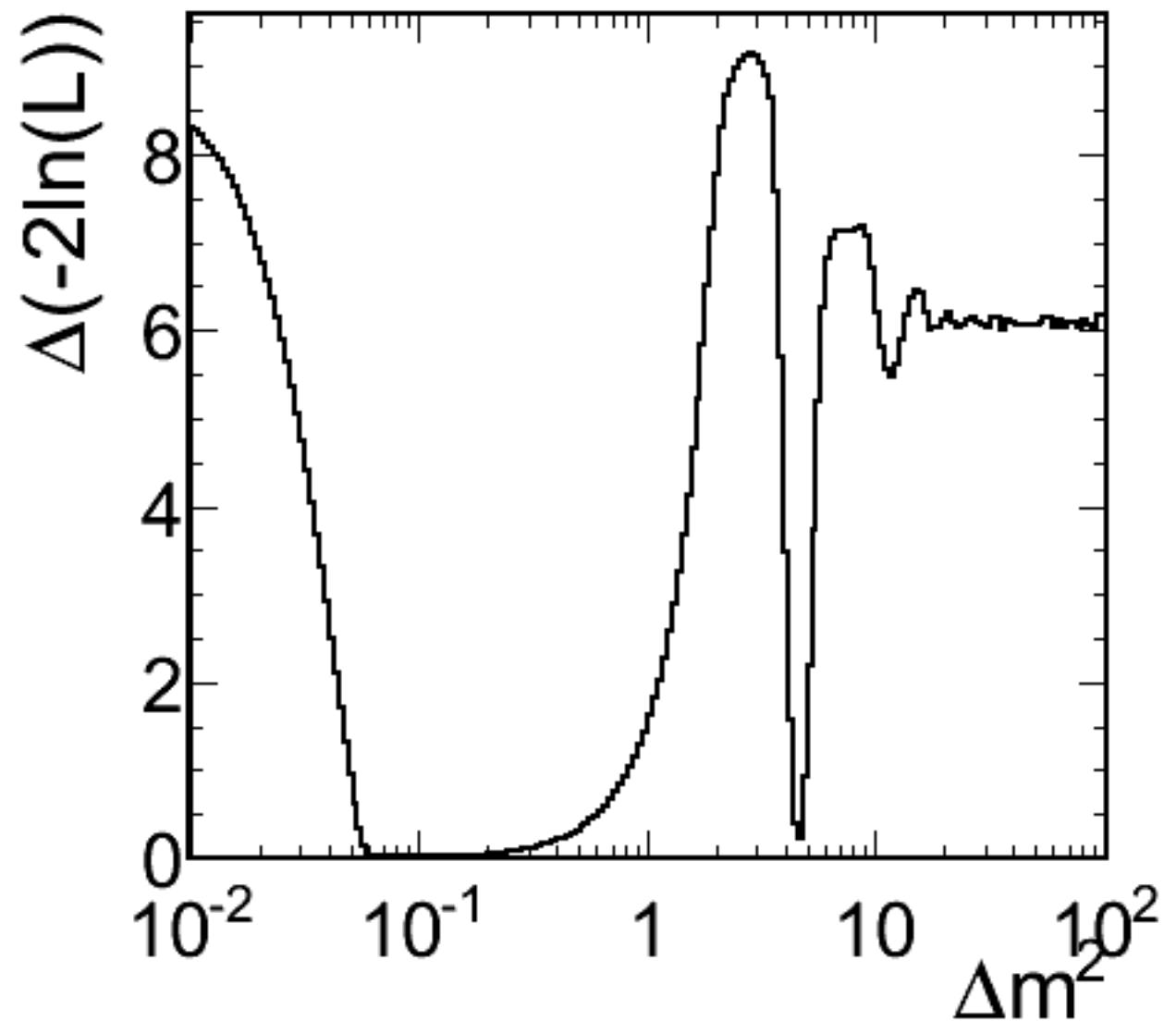
Energy (MeV)	Data	Background	Excess	# σ_{tot}	(# σ_{stat})
200-475	119	100.5+-14.3	18.5+-10.0+-10.2	1.3	(1.9)
475-675	64	38.3+-7.2	25.7+-6.2+-3.7	3.6	(4.1)
475-1250	120	99.1+-14.0	20.9+-10.0+-9.8	1.5	(2.1)
475-3000	158	133.3+-18.0	24.7+-11.5+-13.8	1.4	(2.1)
200-3000	277	233.8+-22.5	43.2+-15.3+-16.5	1.9	(2.8)

MiniBooNE Oscillation Fit E>475

- 5.66E20 POT
- E>475 is signal region for LSND type osc.
- Oscillations favored over background only hypotheses at 99.4% CL (model dependent)
- Best fit ($\sin^2 2\theta$, Δm^2) = (0.9584, 0.064 eV²)
 $\chi^2/NDF = 8.0/4$; Prob. = 8.7% (475-1250 MeV)

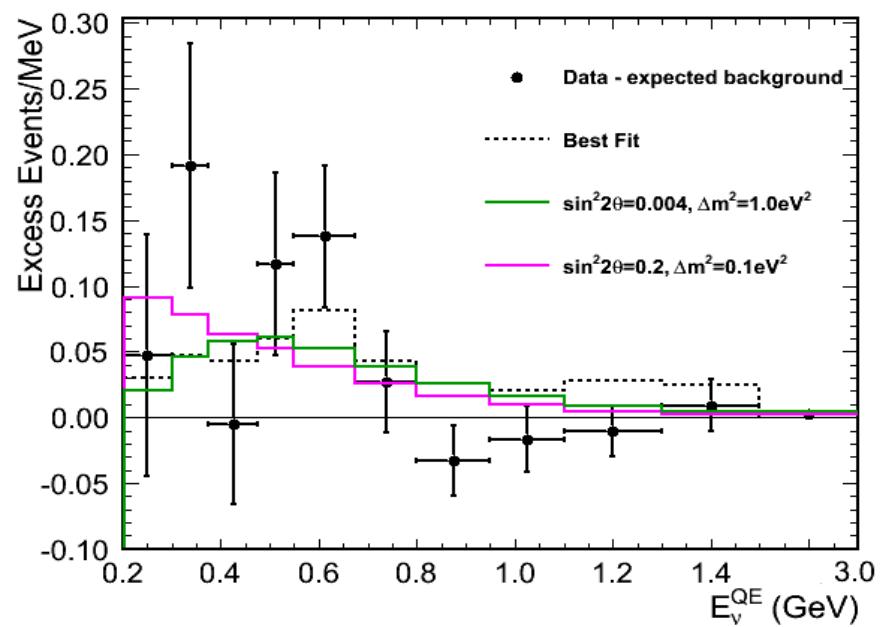
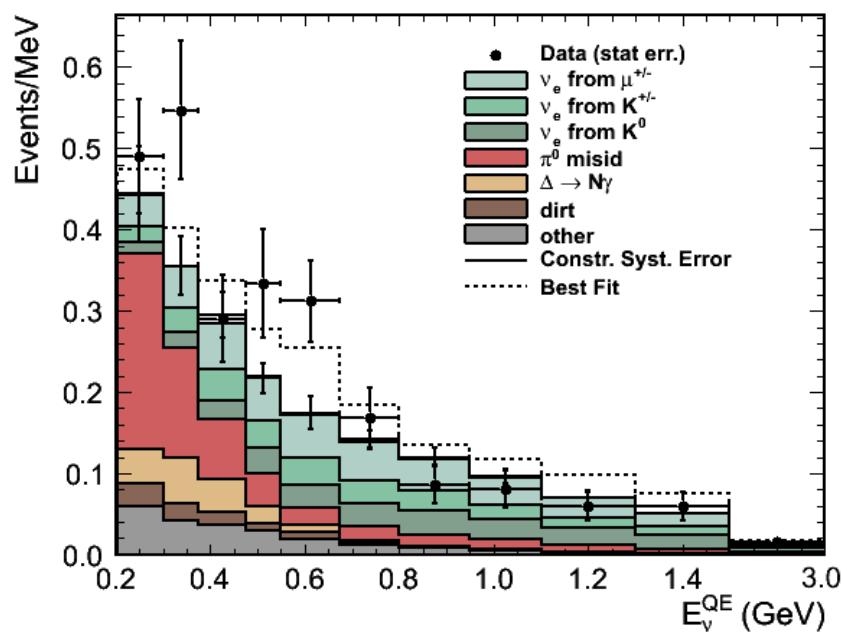
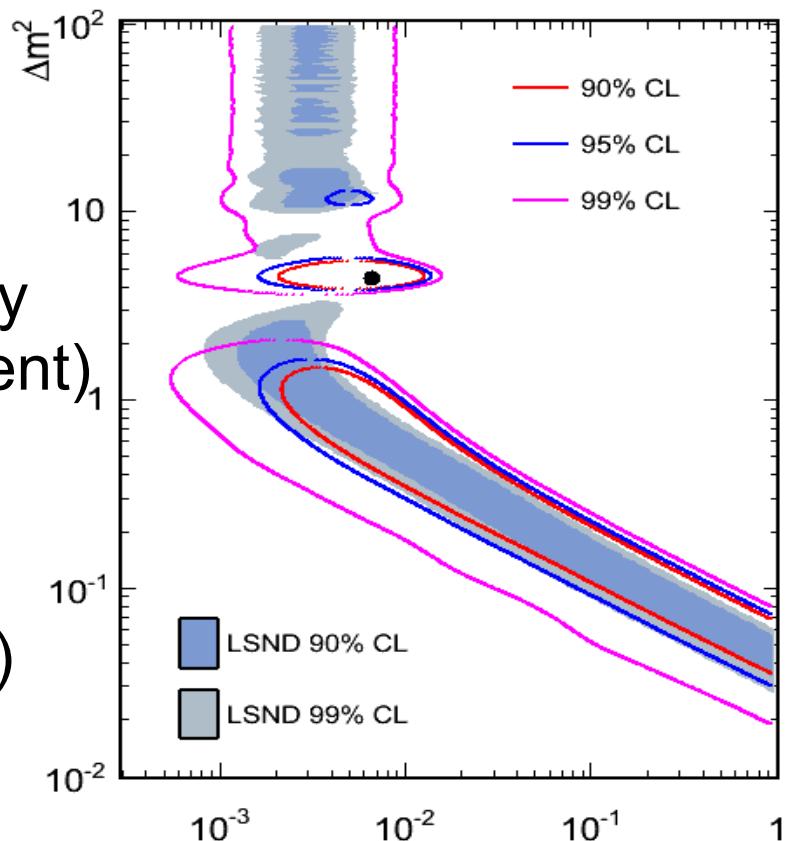


$\Delta\chi^2$ vs Δm^2



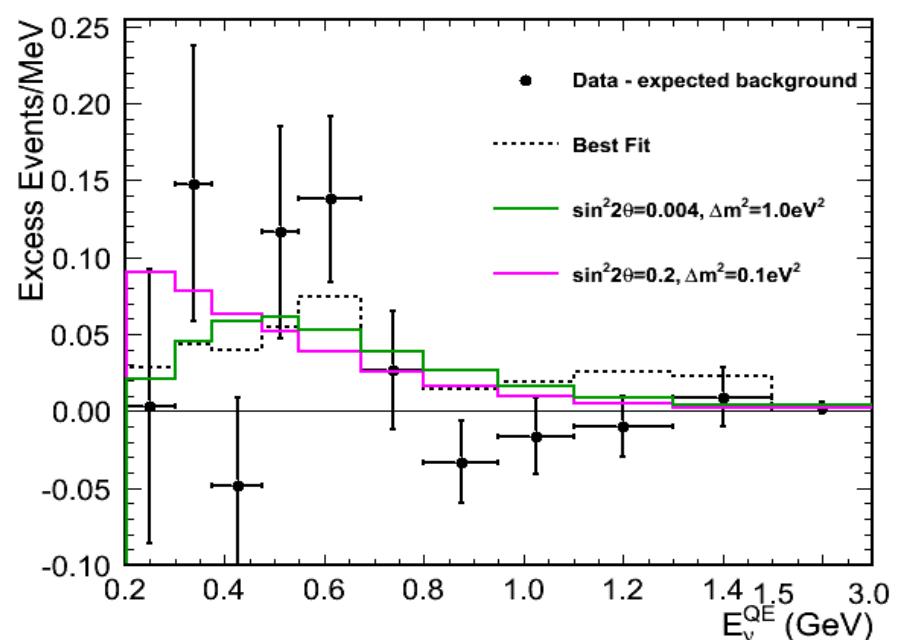
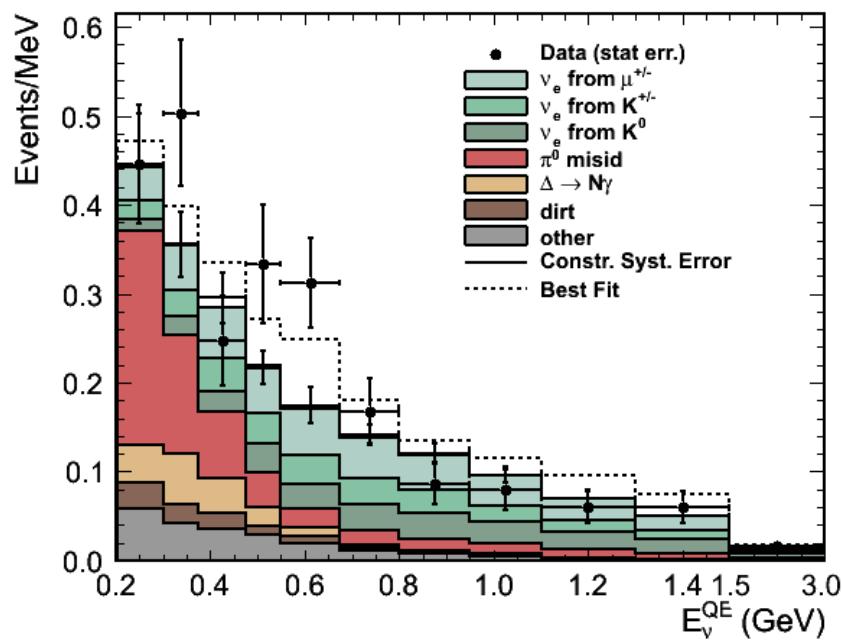
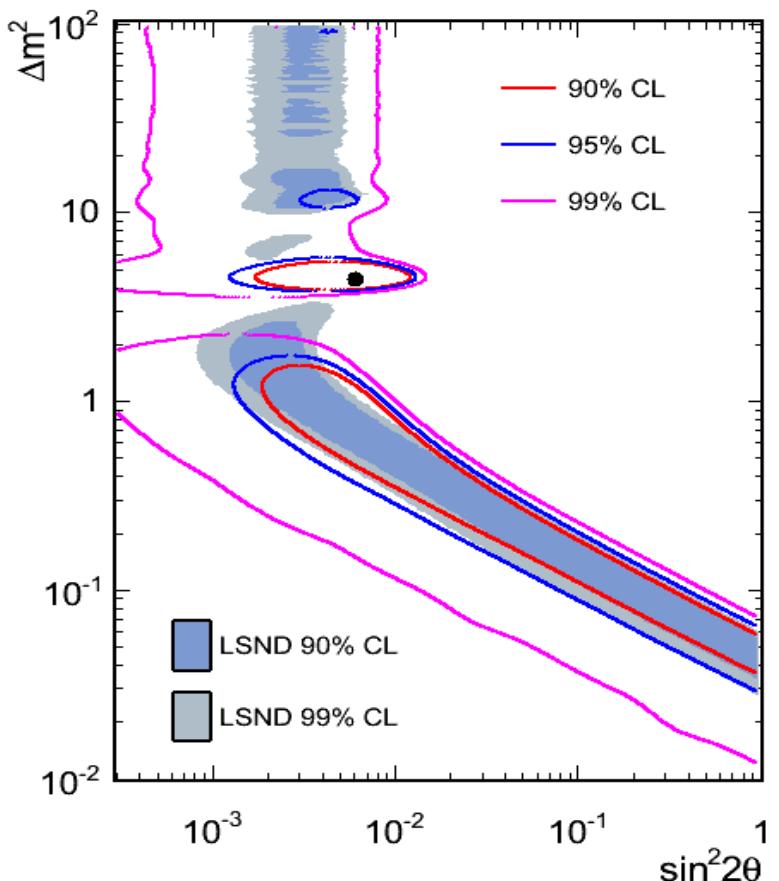
$E > 200\text{MeV}$

- 5.66E20 POT
- Oscillations favored over background only hypotheses at 99.6% CL (model dependent),₁
- No assumption made about low energy excess
- Best fit ($\sin^2 2\theta, \Delta m^2$) = (0.0066, 4.42 eV²)
 $\chi^2/\text{NDF} = 11.6/7$; Prob.=10.9%



$E > 200\text{MeV}$

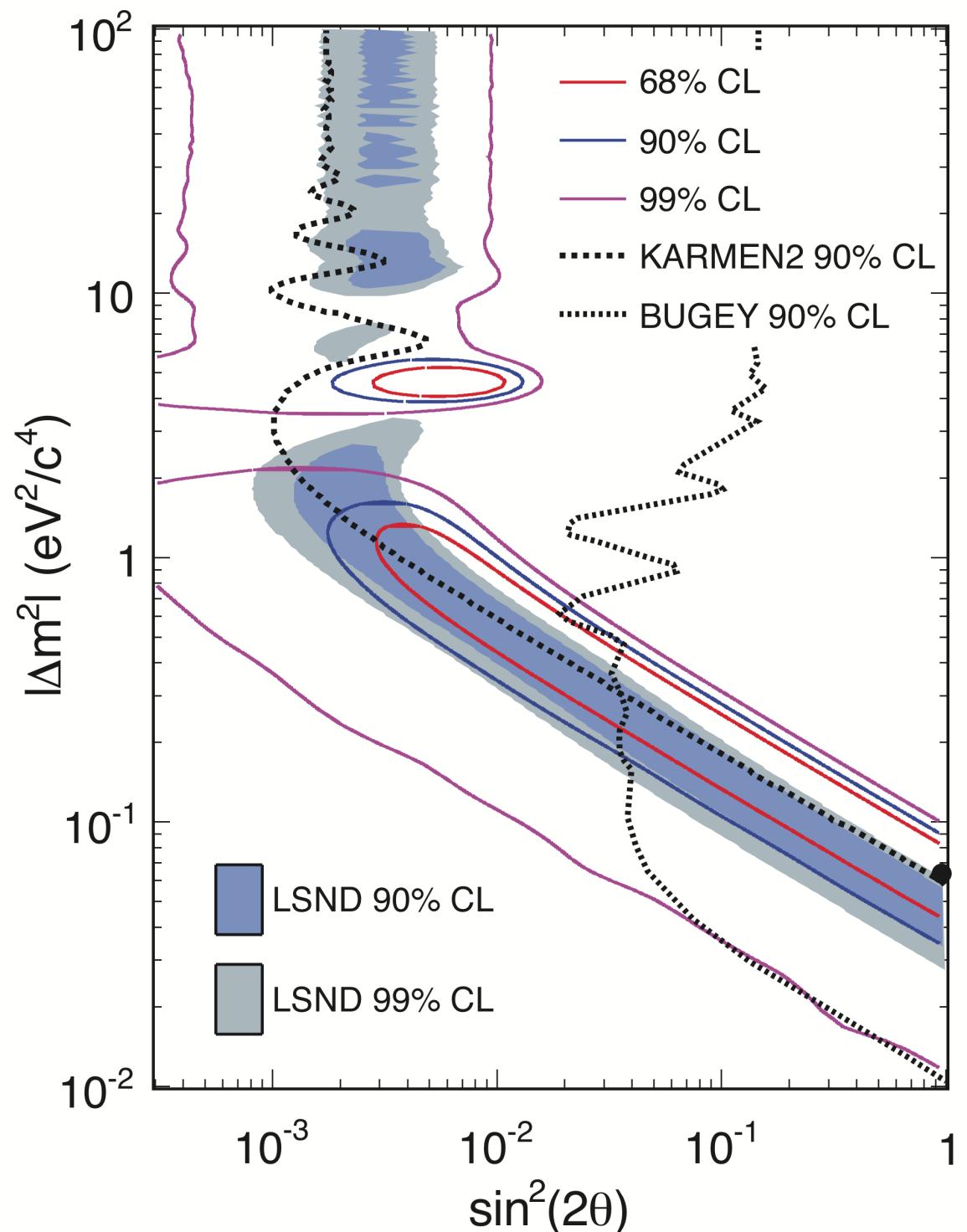
- Subtract excess produced by neutrinos in $\bar{\nu}$ mode (11.6 events)
- Best fit $(\sin^2 2\theta, \Delta m^2) = (0.0061, 4.42 \text{ eV}^2)$
 $\chi^2/\text{NDF} = 12.6/7$; Prob.=7.5%



MiniBooNE Oscillation Fit

$E > 475$ MeV

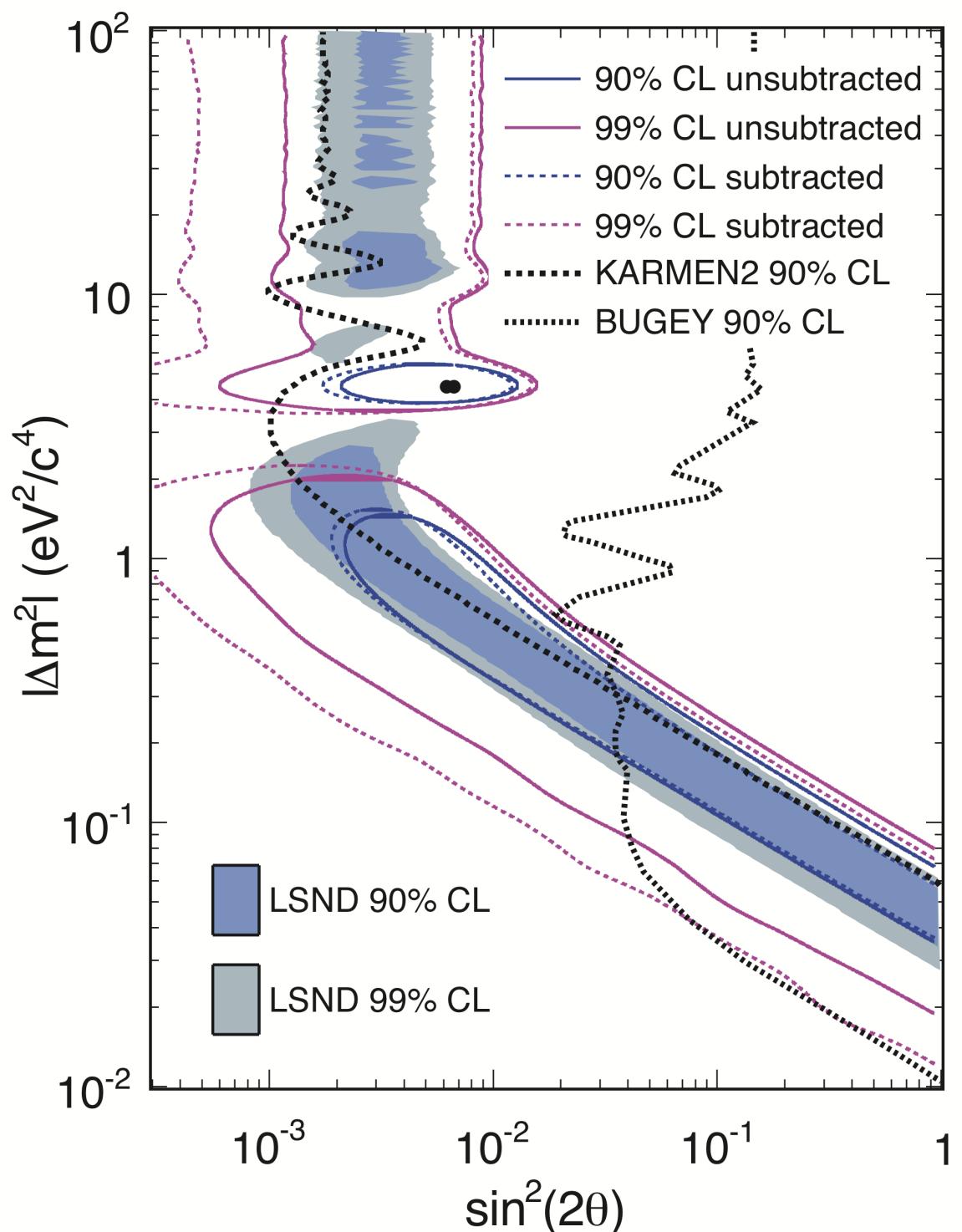
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation results appear to confirm the LSND evidence for antineutrino oscillations, although more data are needed



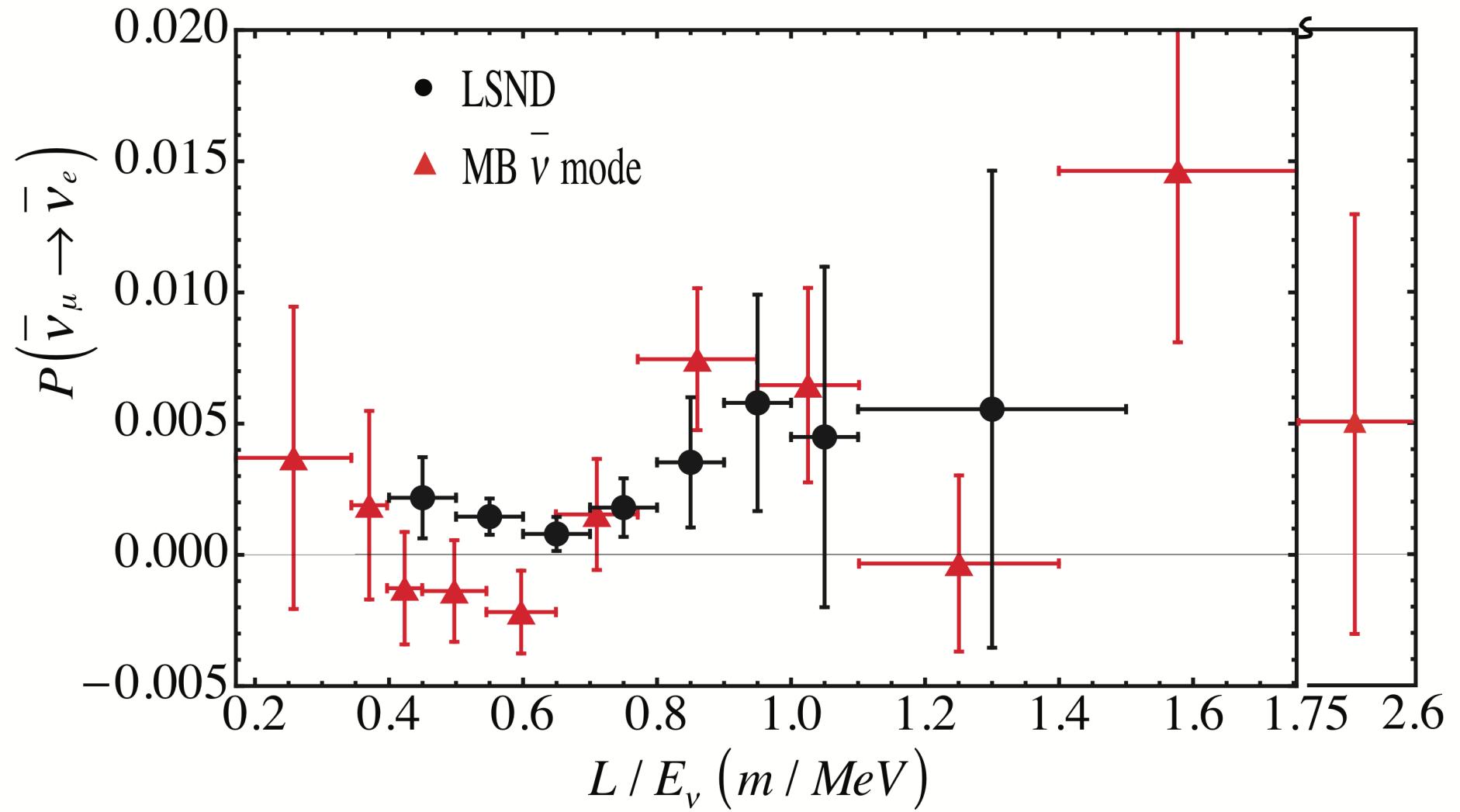
MiniBooNE Oscillation Fit

$E > 200$ MeV

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation results appear to confirm the LSND evidence for antineutrino oscillations, although more data are needed

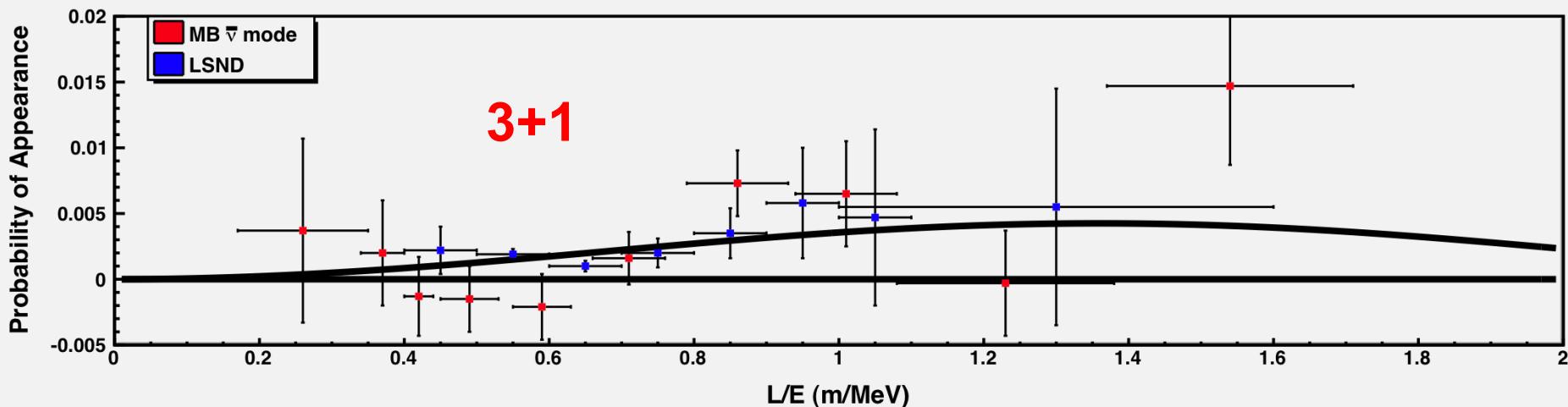


LSND & MiniBooNE Data

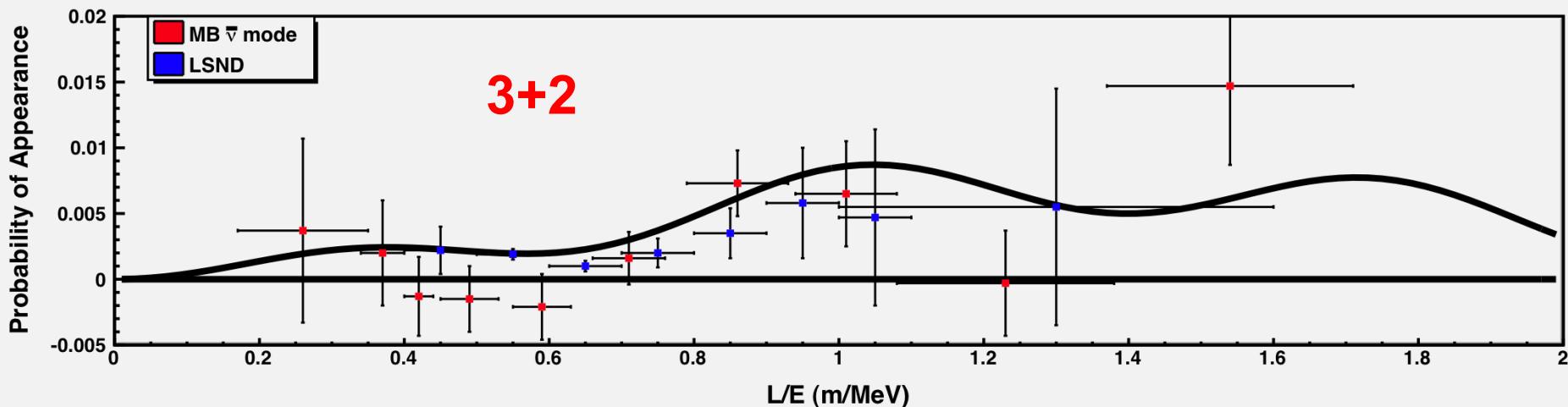


LSND/MiniBooNE Data Compared to 3+N Global Fits

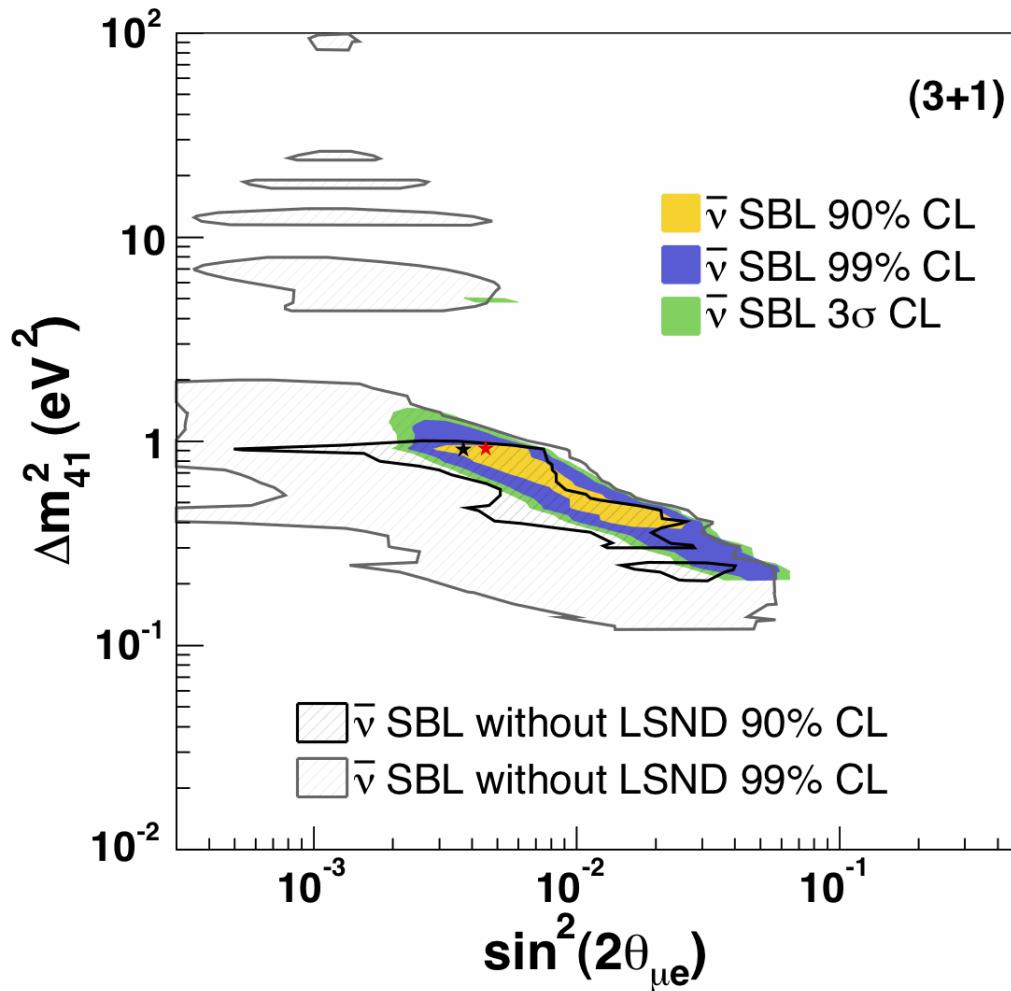
(3+1) $\bar{\nu}_\mu$ Model Antineutrino Appearance



(3+2) $V_b \bar{\nu}_\mu$ Model Antineutrino Appearance



3+1 Global Fit to World Antineutrino Data (with new MiniBooNE data set)

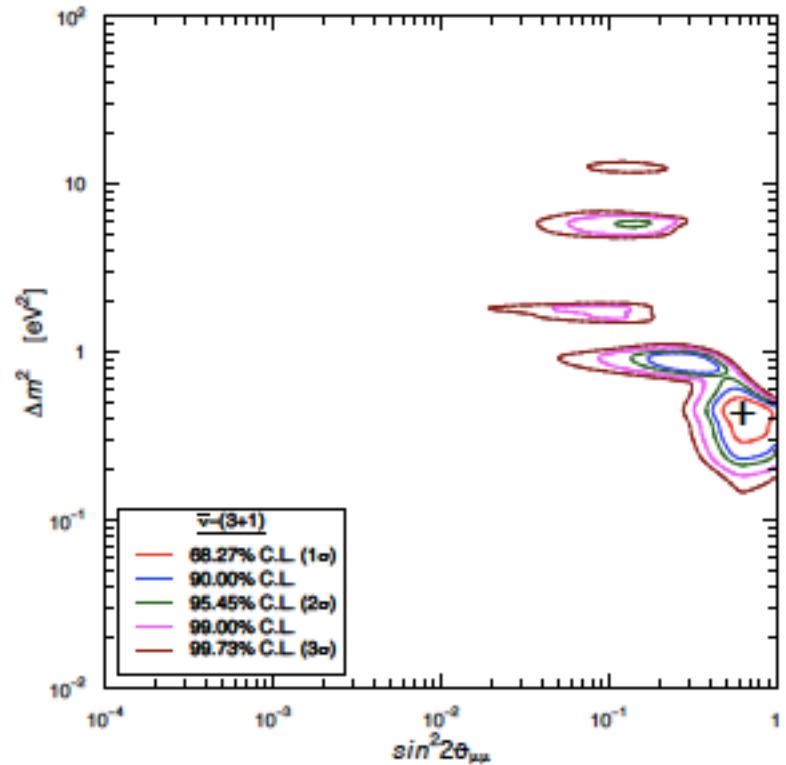
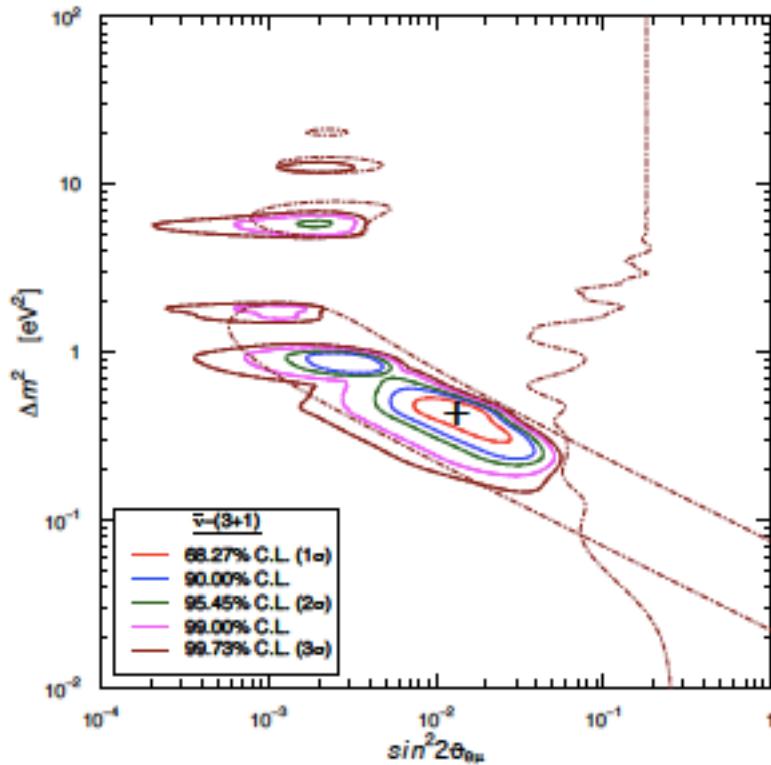


Updated from
G. Karagiorgi et al.,
PRD80, 073001
(2009)

Best 3+1 Fit:
 $\Delta m_{41}^2 = 0.92 \text{ eV}^2$
 $\sin^2 2\theta_{\mu e} = 0.0045$
 $\chi^2 = 85.0/103 \text{ DOF}$
Prob. = 90%

Predicts $\bar{\nu}_\mu$ & $\bar{\nu}_e$ disappearance of
 $\sin^2 2\theta_{\mu\mu} \sim 37\%$ and
 $\sin^2 2\theta_{ee} \sim 4.3\%$

Antineutrino Oscillations in 3+1 Schemes



$$\chi^2_{\min} = 77.5$$

$$\text{NdF} = 82$$

$$\text{GoF} = 62\%$$

$$\Delta m^2 = 0.43 \text{ eV}^2$$

$$\sin^2 2\vartheta_{e\mu} = 0.013$$

$$\sin^2 2\vartheta_{ee} = 0.017$$

$$\sin^2 2\vartheta_{\mu\mu} = 0.63$$

Prediction: large SBL $\bar{\nu}_\mu$ disappearance at $0.1 \lesssim \Delta m^2 \lesssim 1 \text{ eV}^2$

3+N Models Requires Large $\bar{\nu}_\mu$ Disappearance!

In general, $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) < \frac{1}{4} P(\bar{\nu}_\mu \rightarrow \bar{\nu}_x) P(\bar{\nu}_e \rightarrow \bar{\nu}_x)$

Reactor Experiments: $P(\bar{\nu}_e \rightarrow \bar{\nu}_x) < 5\%$

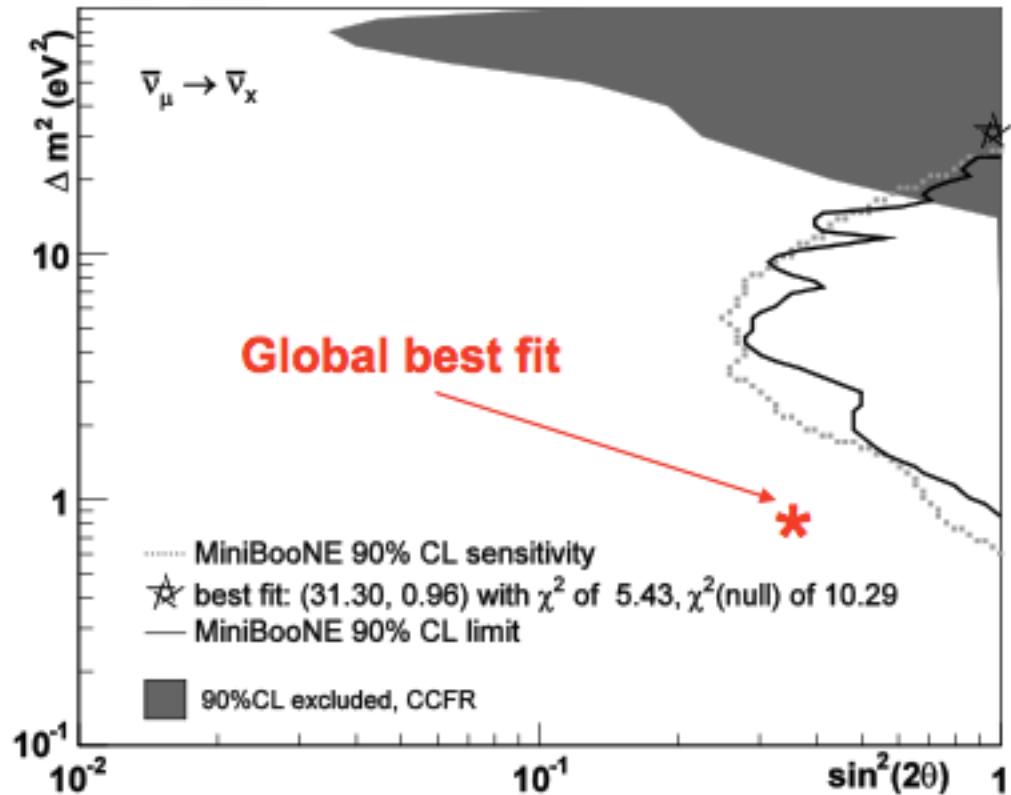
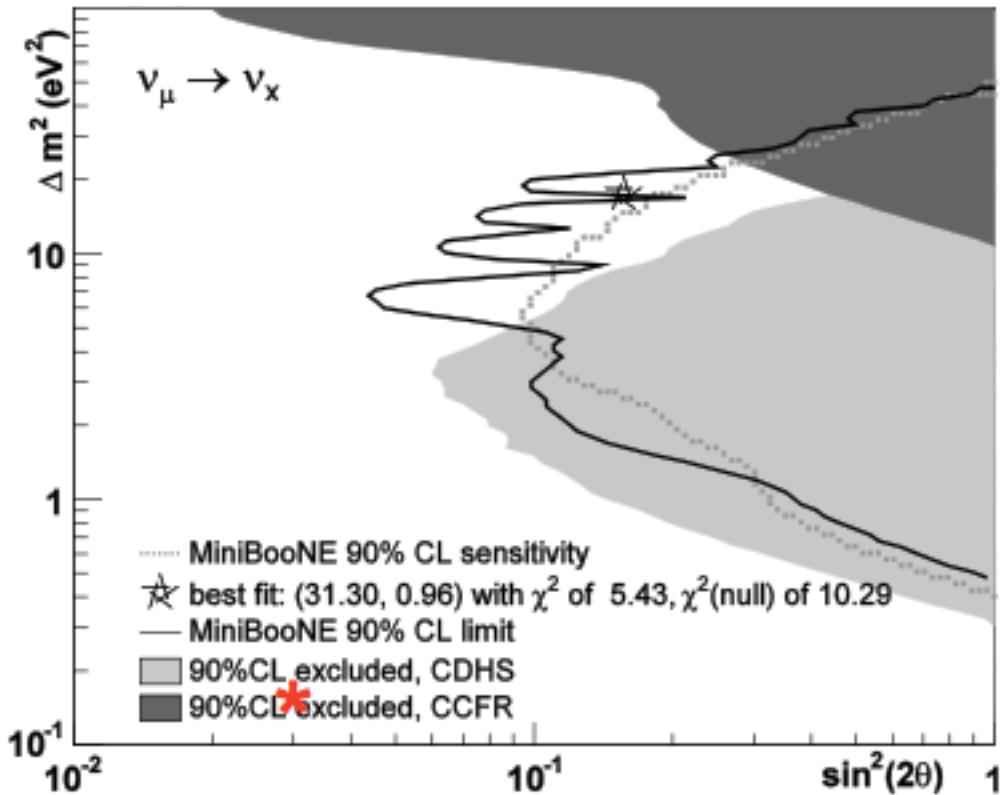
LSND/MiniBooNE: $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \sim 0.25\%$

Therefore: $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_x) > 20\%$

Assuming that the 3 light neutrinos are mostly active
and the N heavy neutrinos are mostly sterile.

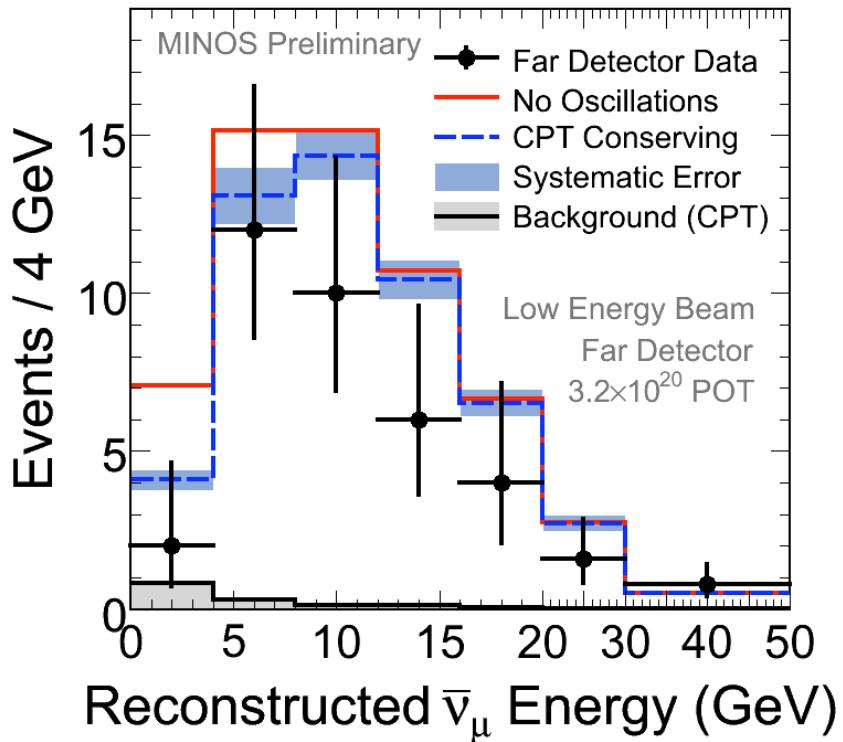
MiniBooNE Neutrino & Antineutrino Disappearance Limits

A.A. Aguilar-Arevalo et al., PRL 103, 061802 (2009)

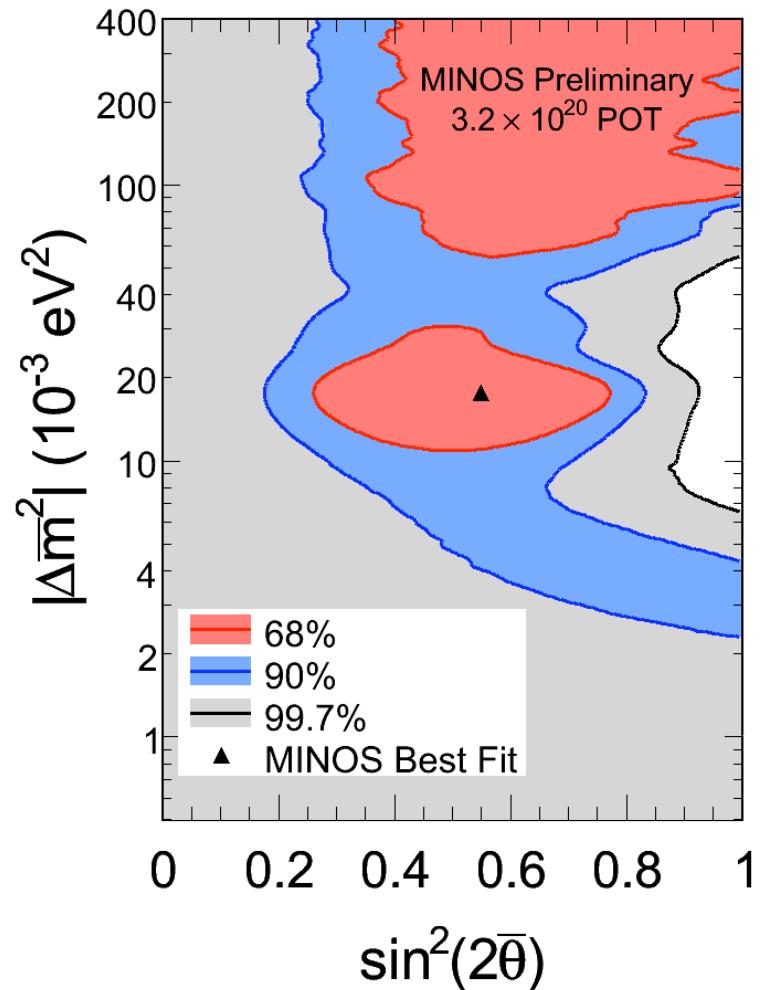


Improved results soon from MiniBooNE/SciBooNE Joint Analysis!

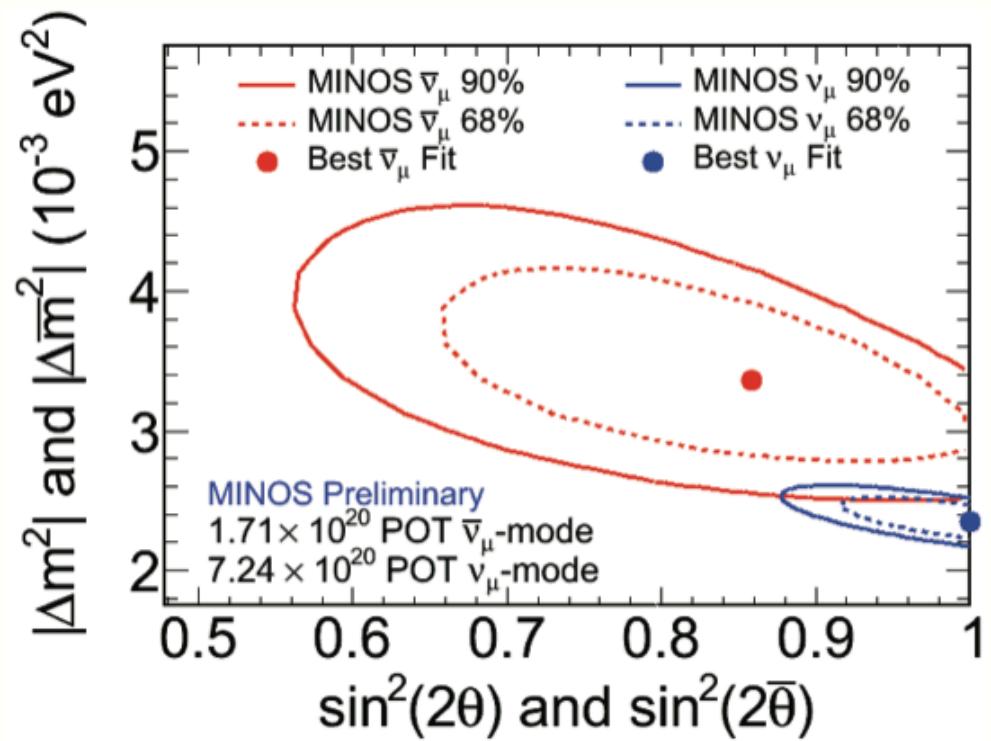
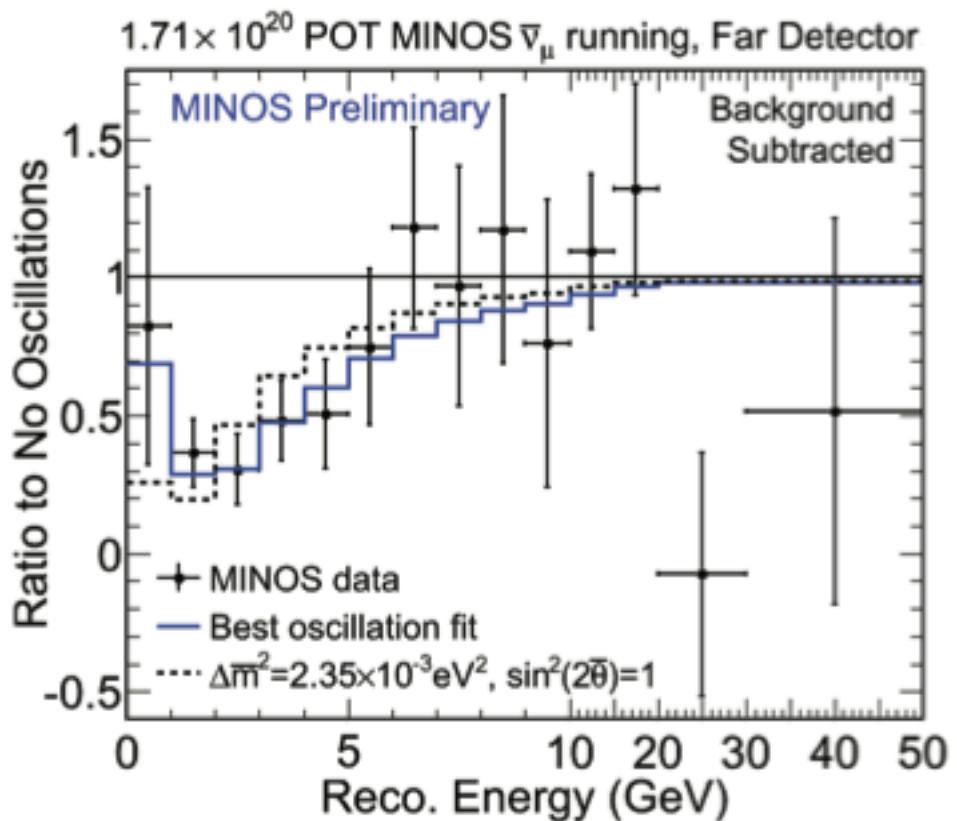
Initial MINOS $\bar{\nu}_\mu$ Disappearance Results in ν Mode



Expect $\bar{\nu}_\mu$ disappearance above 10 GeV for LSND neutrino oscillations.



Initial MINOS $\bar{\nu}_\mu$ Disappearance Results in $\bar{\nu}$ Mode



Expect $\bar{\nu}_\mu$ disappearance above
10 GeV for LSND neutrino oscillations.

IceCube Atmospheric Neutrino Angular Distribution

arXiv:1010.3980 (40 strings; 12 months of data)

IceCube covers the range of $0.001 < L/E < 100$ m/MeV !

+ Matter
Effects can
enhance
Oscillations

70% neutrino +
30% antineutrino

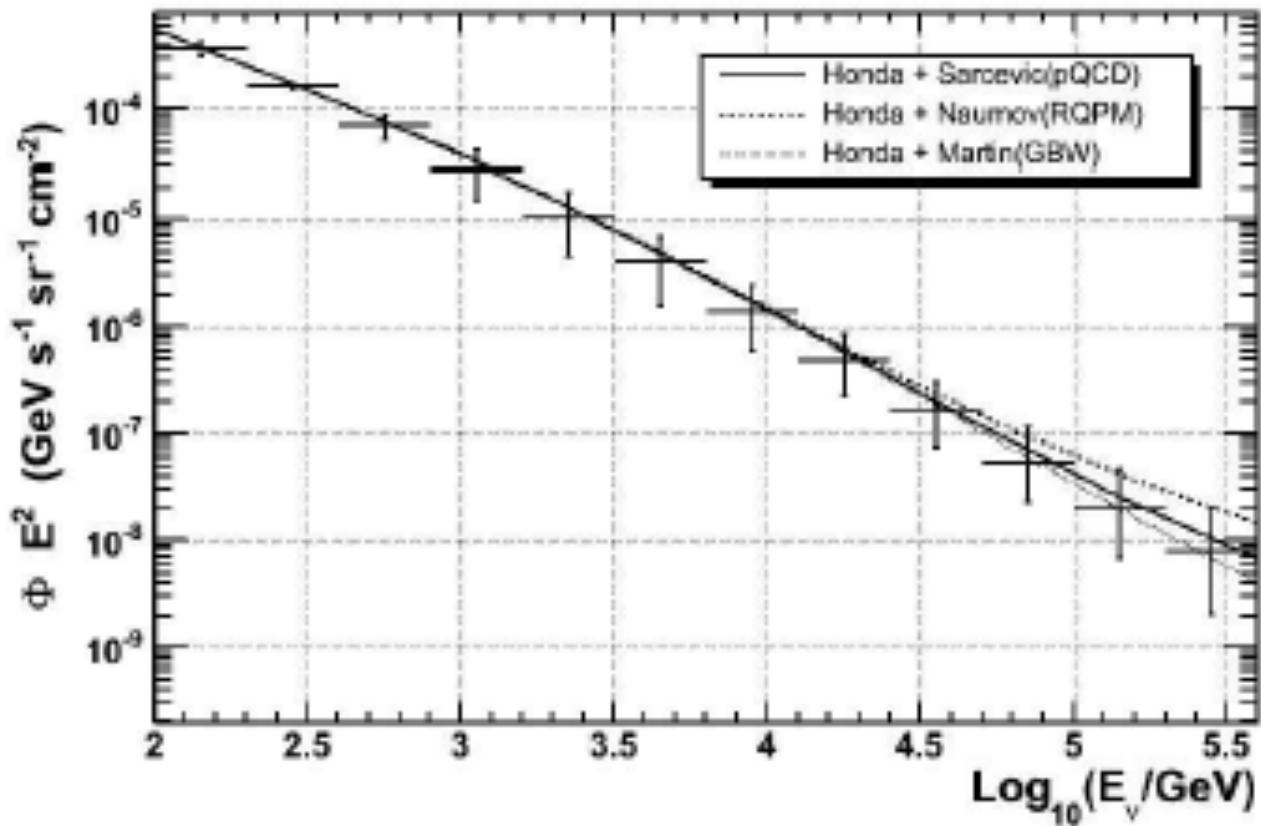


FIG. 24: Comparison of various prompt flux models to the unfolded result. The models shown are the sum of the Honda flux [2], plus one of Sarcevic [8], Naumov [10], or Martin [9].

IceCube Atmospheric Neutrino Angular Distribution

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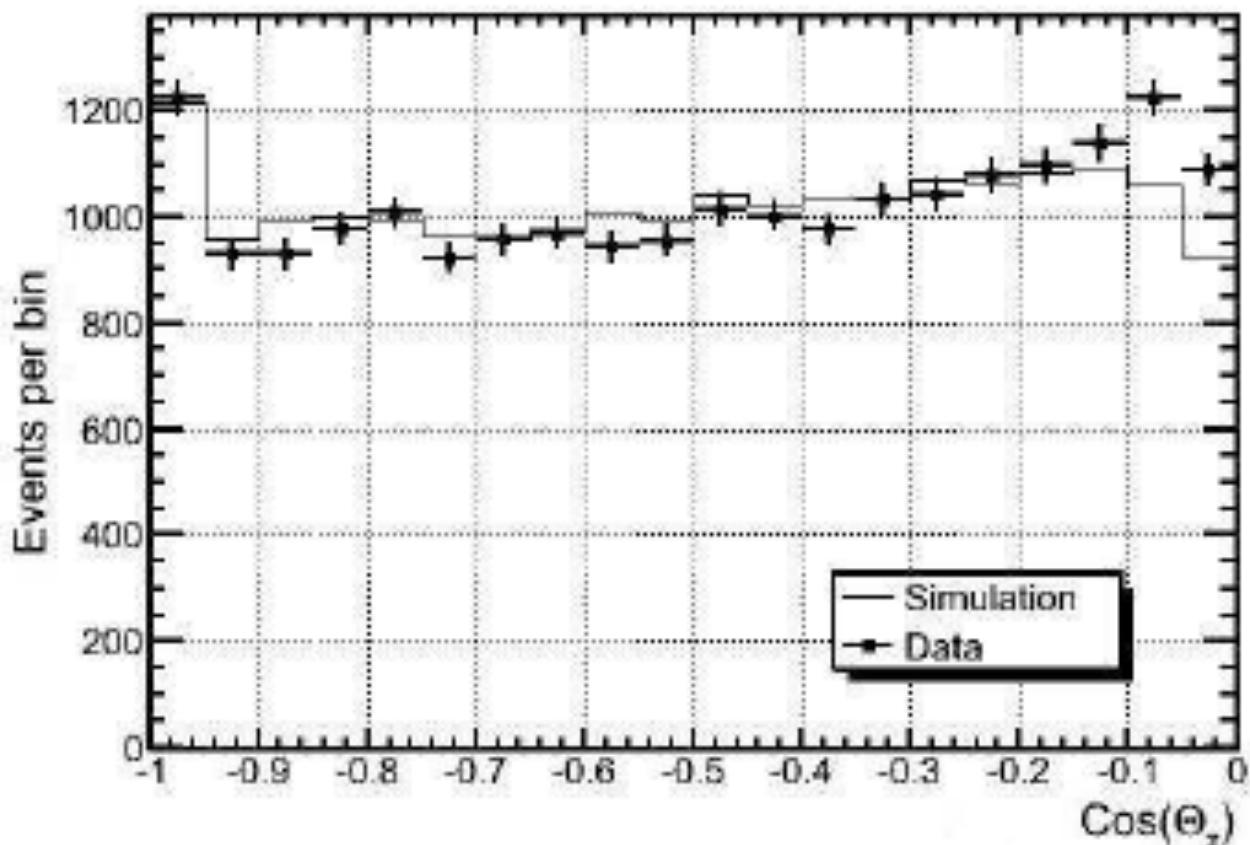
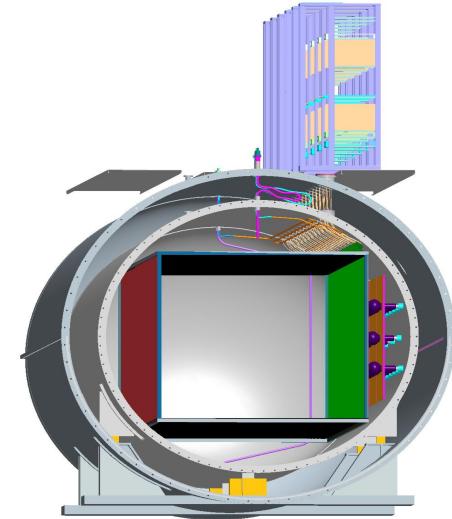


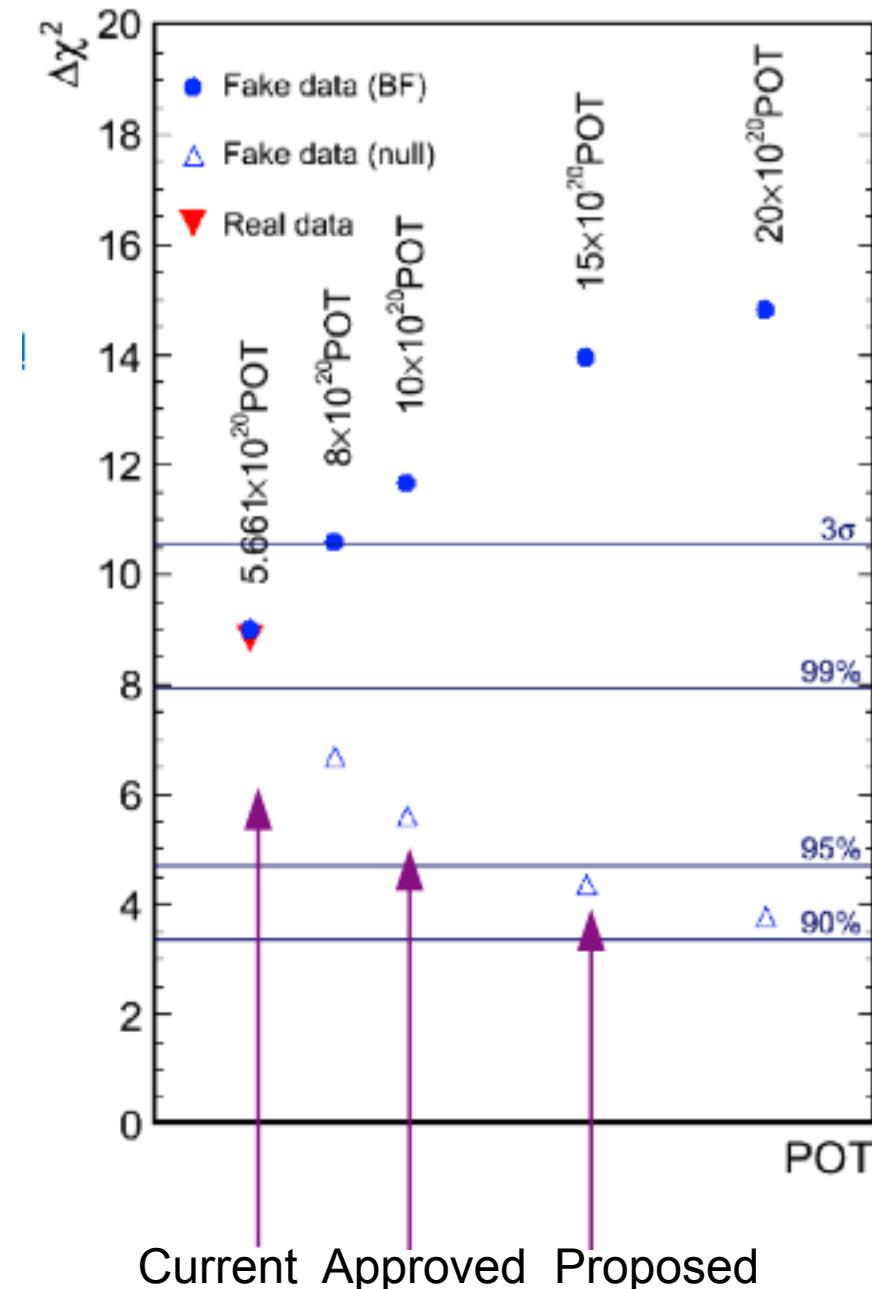
FIG. 19: $\text{Cosine}(\theta_Z)$ distributions for data and for simulation, using zenith angle from the MPE fit. Simulation has been normalized to the data. Error bars for data are statistical only.

Future Experiments

- More MiniBooNE $\bar{\nu}$ Data (15E20 POT)
- MicroBooNE
 - CD1 approved
 - Address low energy excess
 - Two MicroBooNE detectors?
- NOvA: 2 near detectors?
- Few ideas under consideration:
 - Move or build a MiniBooNE like detector at 200m (LOI arXiv:0910.2698)
 - A new search for anomalous neutrino oscillations at the CERN-PS (arxiv:0909.0355v3)
 - Redoing a stopped pion source at ORNL (OscSNS - <http://physics.calumet.purdue.edu/~oscsns/>)



More MiniBooNE Antineutrino Running



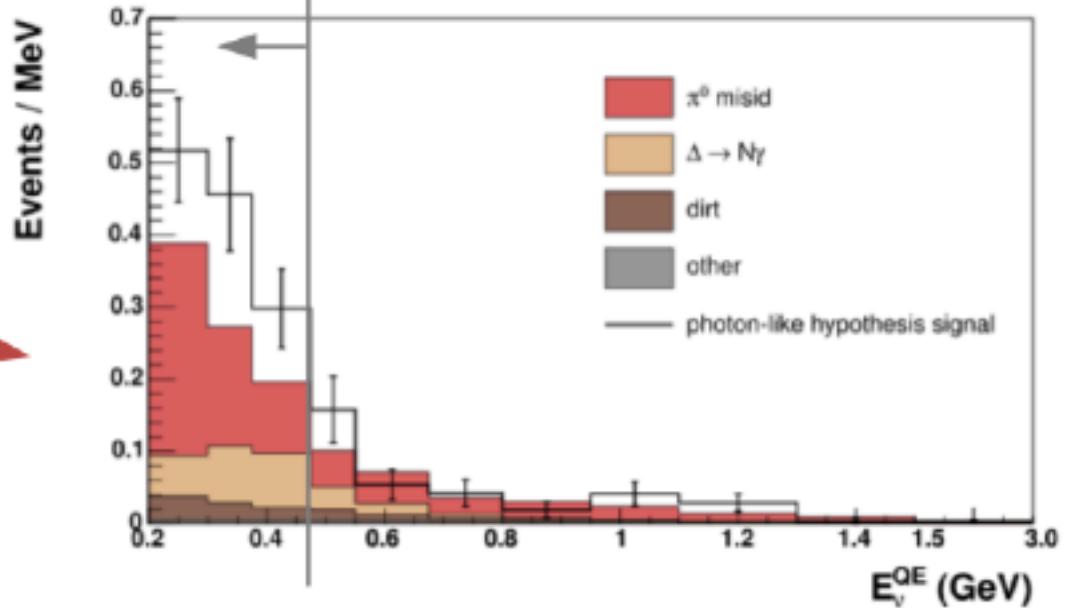
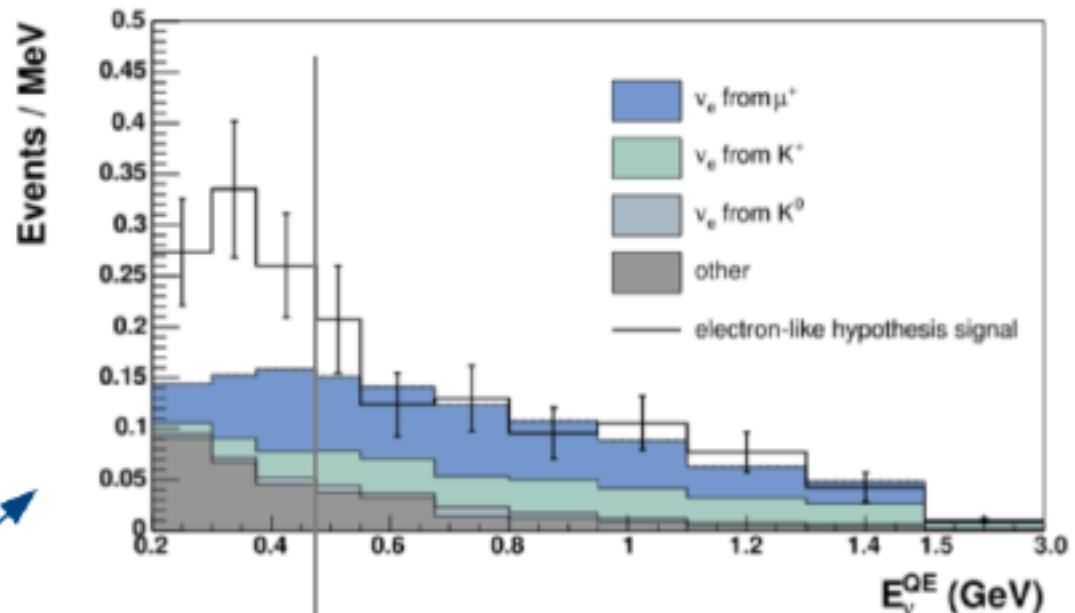
MicroBooNE

MicroBooNE sensitivity to low energy excess:

(neutrino running,
70 ton fiducial volume,
x2 higher PID efficiency
than MiniBooNE,
3% mis-ID,
6.0e20 POT)

Electron-like hypothesis:
36.8 excess events
41.6 background events
5.7 σ stat. significance

Photon-like hypothesis:
36.8 excess events
78.9 background events
4.1 σ stat. significance

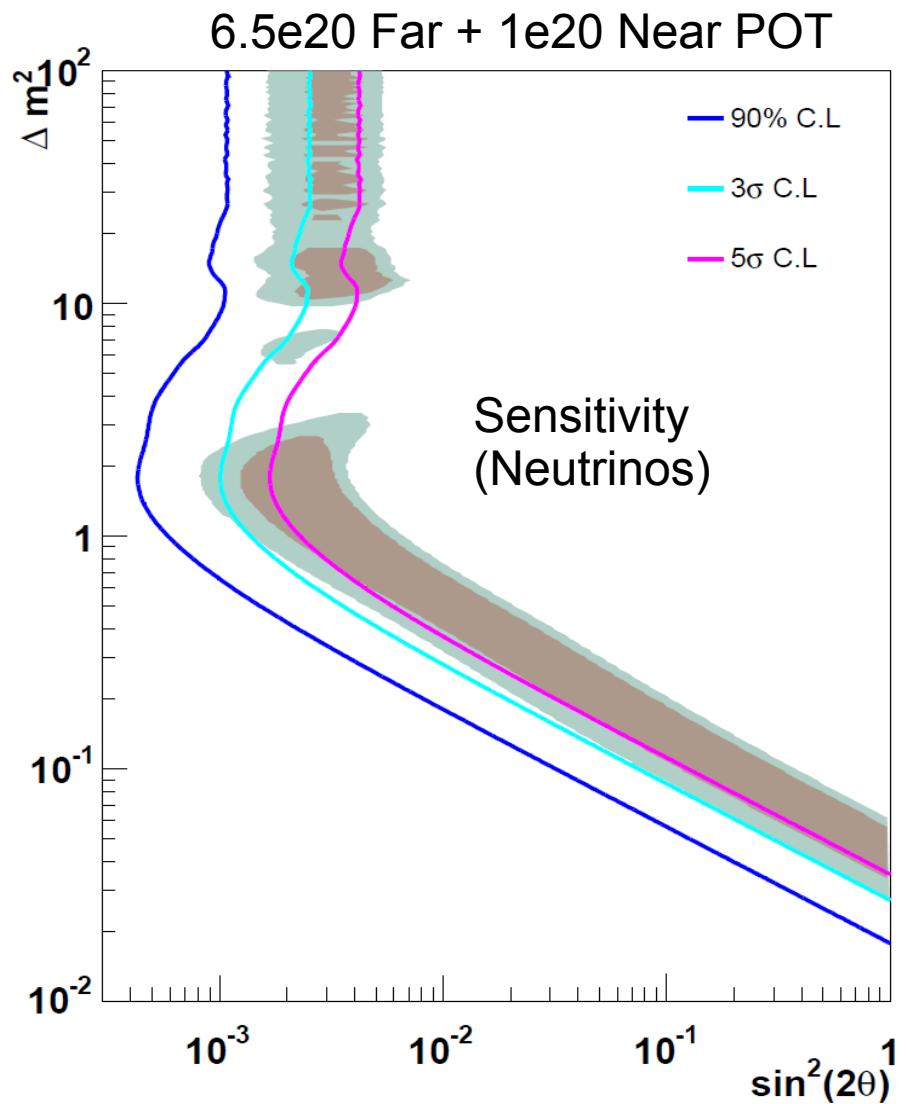


BooNE: Near Detector at ~200 m



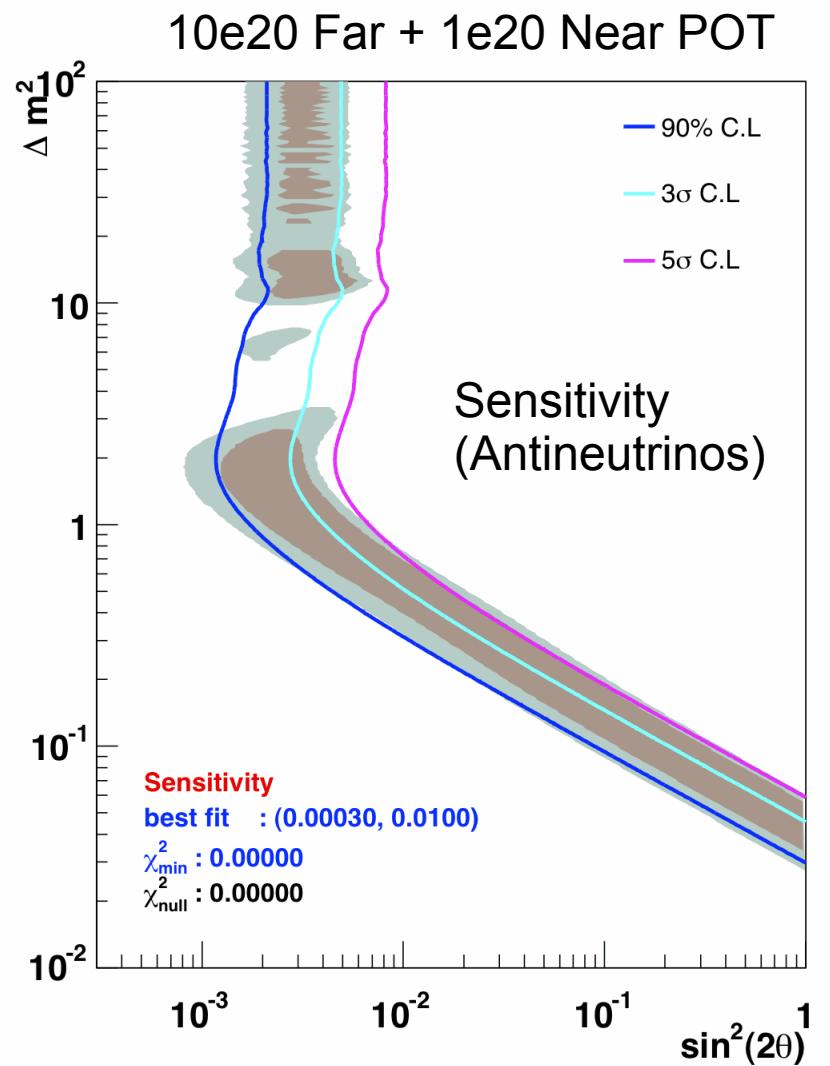
BooNE

- MiniBooNE like detector at 200m
- Flux, cross section and optical model errors cancel in 200m/500m ratio analysis
- Gain statistics quickly, already have far detector data
- Measure $\nu_\mu \rightarrow \nu_e$ & $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations and CP violation



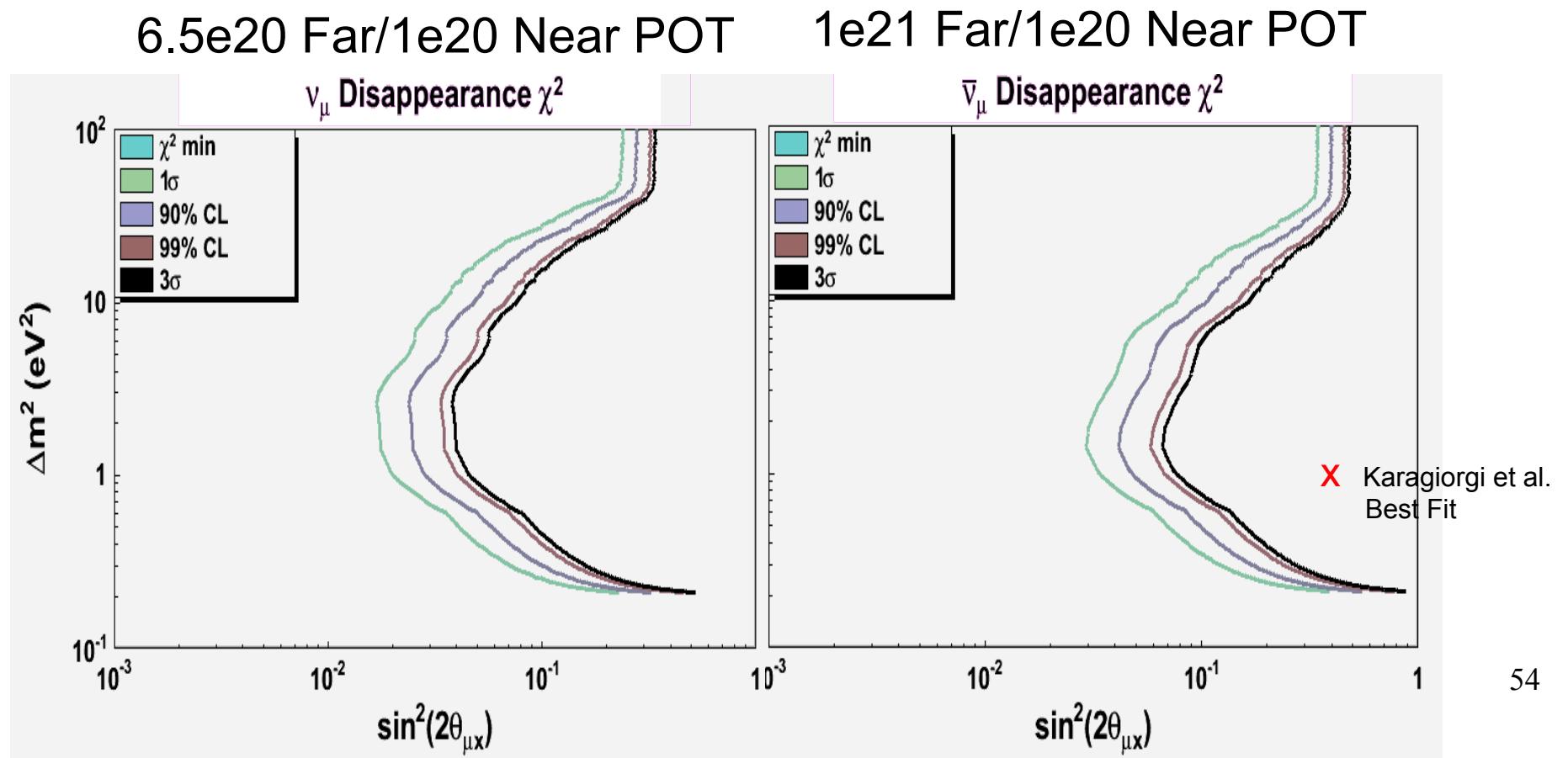
BooNE

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BooNE

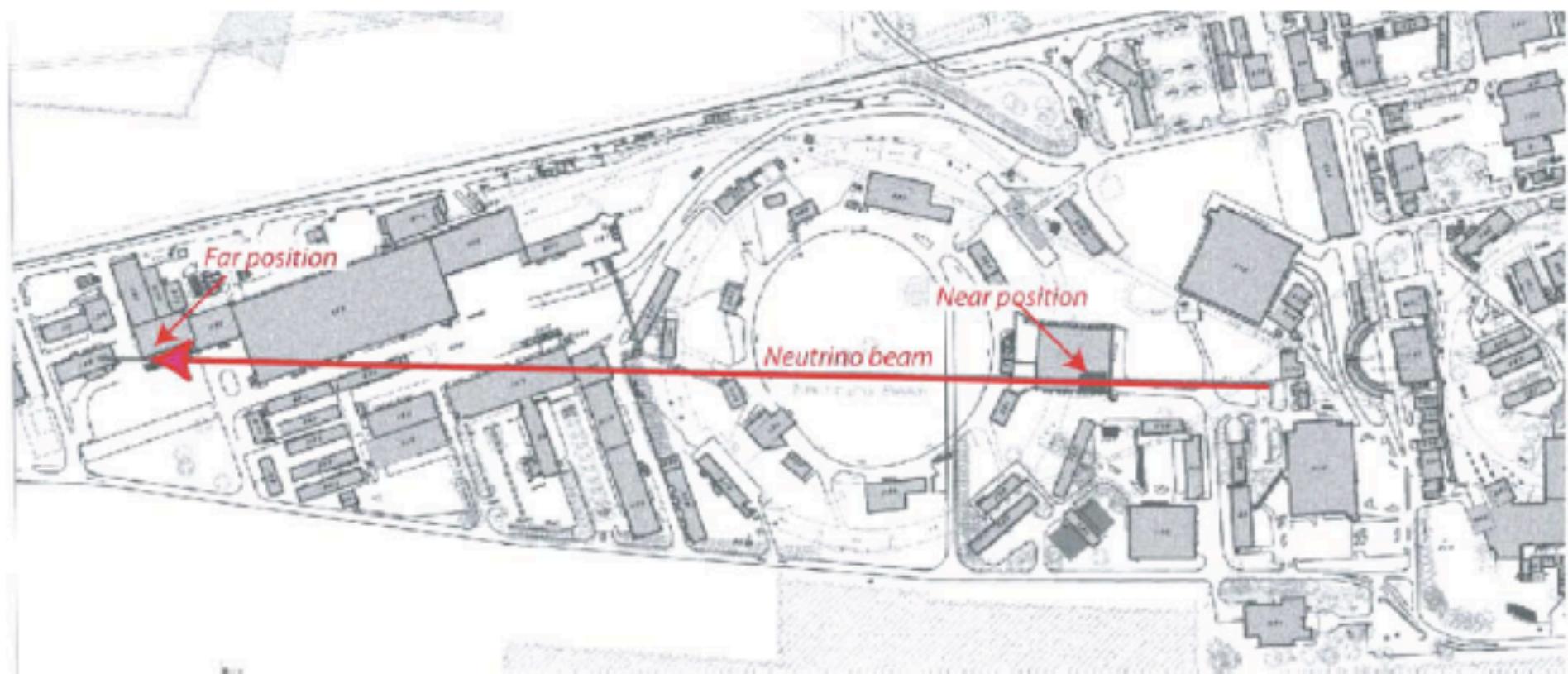
- Much better sensitivity for ν_μ & $\bar{\nu}_\mu$ disappearance
- Look for CPT violation ($\nu_\mu \rightarrow \nu_\mu \neq \bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$)



ICARUS at the CERN PS

A new search for anomalous neutrino oscillations at the CERN-PS

B. Baibussinov^a, E. Calligarich^b S. Centro^a, D. Gibin^a, A. Guglielmi^a,
F. Pietropaolo^a, C. Rubbia^{c,*} and P. Sala^d



ICARUS at the CERN PS

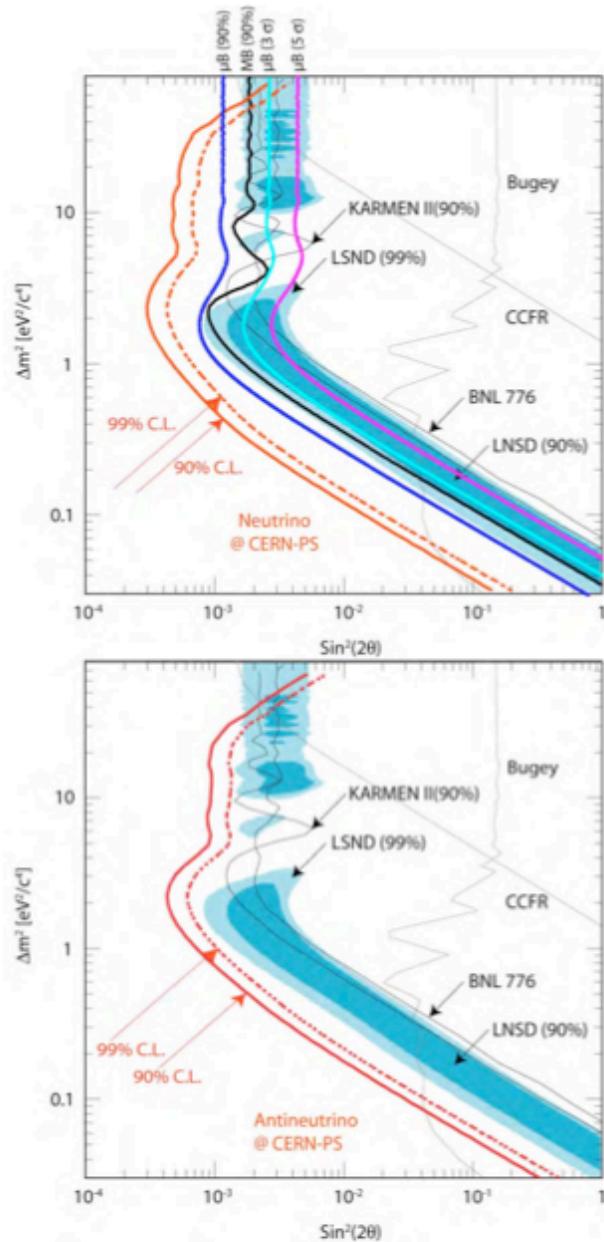


Figure 25. Expected sensitivity for the proposed experiment exposed at the CERN-PS neutrino beam (top) and anti-neutrino (bottom) for 2.5×10^{29} pot and 5.0×10^{29} pot respectively. The LSND allowed region is fully explored in both cases.



Figure 7. The ICARUS T600 detector installed in Hall B at LNGS.

600 ton ICARUS at 850 m

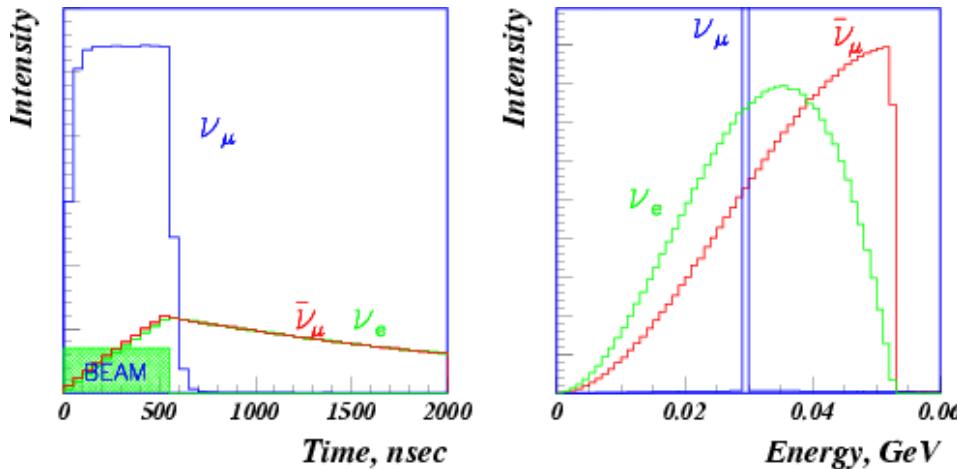
150 ton LAr at 127 m

OscSNS

- Spallation neutron source at ORNL
- 1GeV protons on Hg target (1.4MW)
- Free source of neutrinos
- Well understood flux of neutrinos



OscSNS



$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ $\Delta(L/E) \sim 3\%$; $\bar{\nu}_e p \rightarrow e^+ n$

$\nu_\mu \rightarrow \nu_e$ $\Delta(L/E) \sim 3\%$; $\nu_e C \rightarrow e^+ N_{gs}$

$\nu_\mu \rightarrow \nu_s$ $\Delta(L/E) < 1\%$; **Monoenergetic ν_μ !**; $\nu_\mu C \rightarrow \nu_\mu C^*(15.11)$

$\bar{\nu}_\mu \rightarrow \bar{\nu}_s$; $\bar{\nu}_\mu C \rightarrow \bar{\nu}_\mu C^*(15.11)$

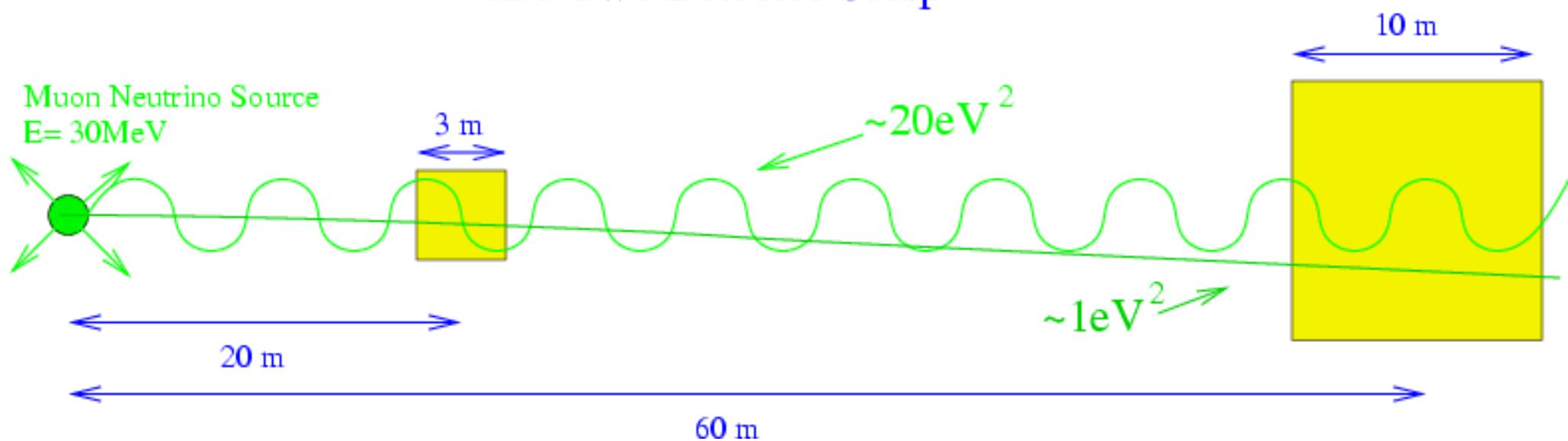
OscSNS would be capable of making precision measurements of $\bar{\nu}_e$ appearance & ν_u disappearance and proving, for example, the existence of sterile neutrinos! (see Phys. Rev. D72, 092001 (2005)).

Search for Sterile Neutrinos with OscSNS Via Measurement of NC Reaction:

$$\nu_\mu \text{ C} \rightarrow \nu_\mu \text{ C}^*(15.11)$$

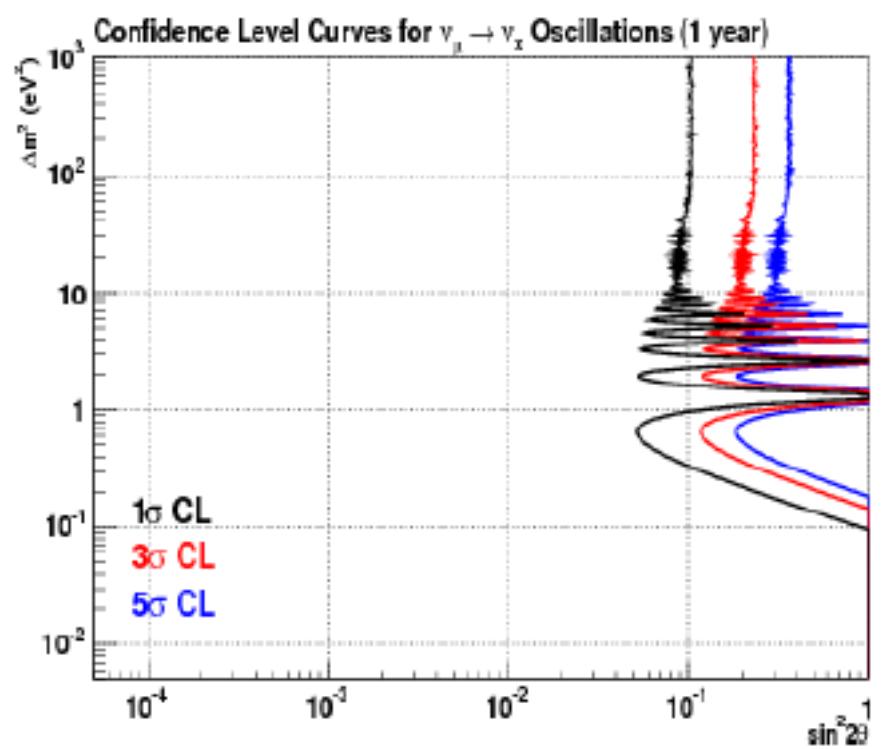
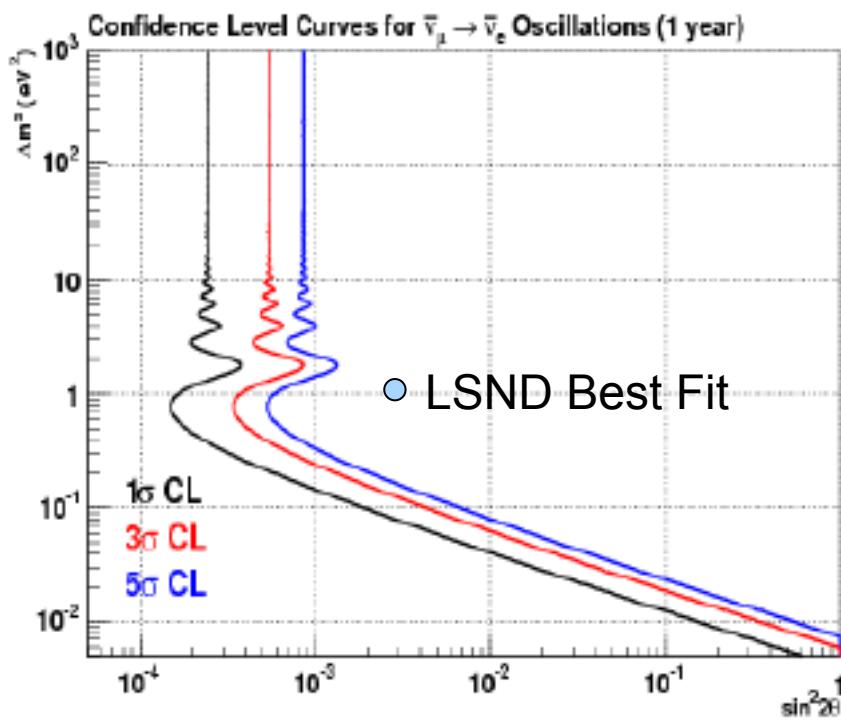
Garvey et al., Phys. Rev. D72 (2005) 092001

Neutral Current Disappearance Pattern
in a Two Detector Setup



OscSNS

- $\bar{\nu}_e$ appearance (left) and ν_μ disappearance sensitivity (right) for 1 year of running (for 60m!)

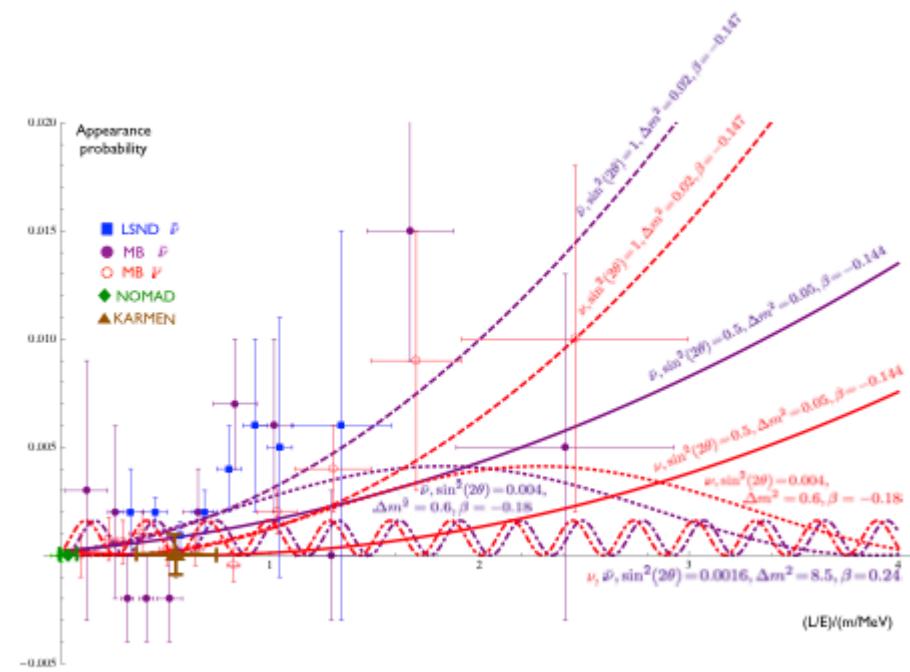
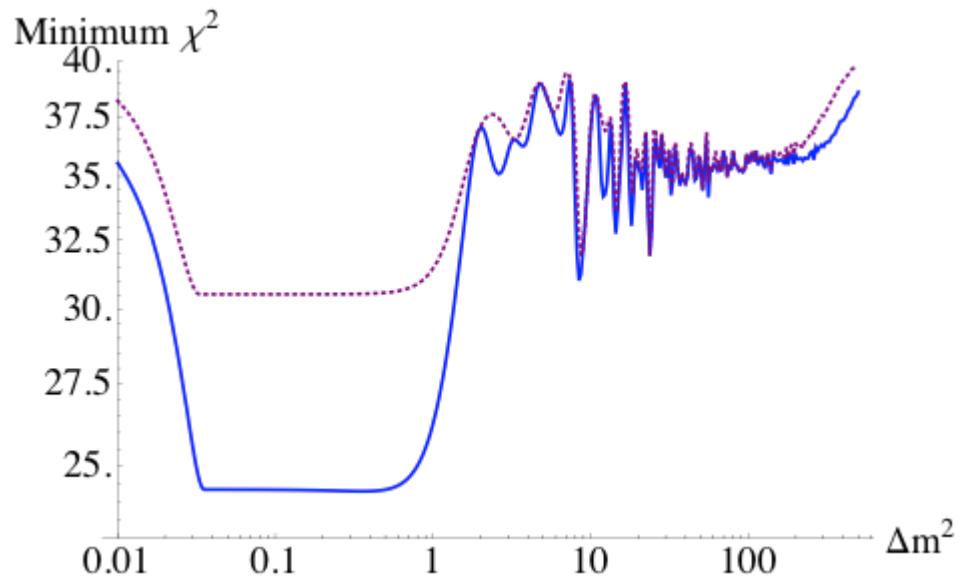


Conclusions

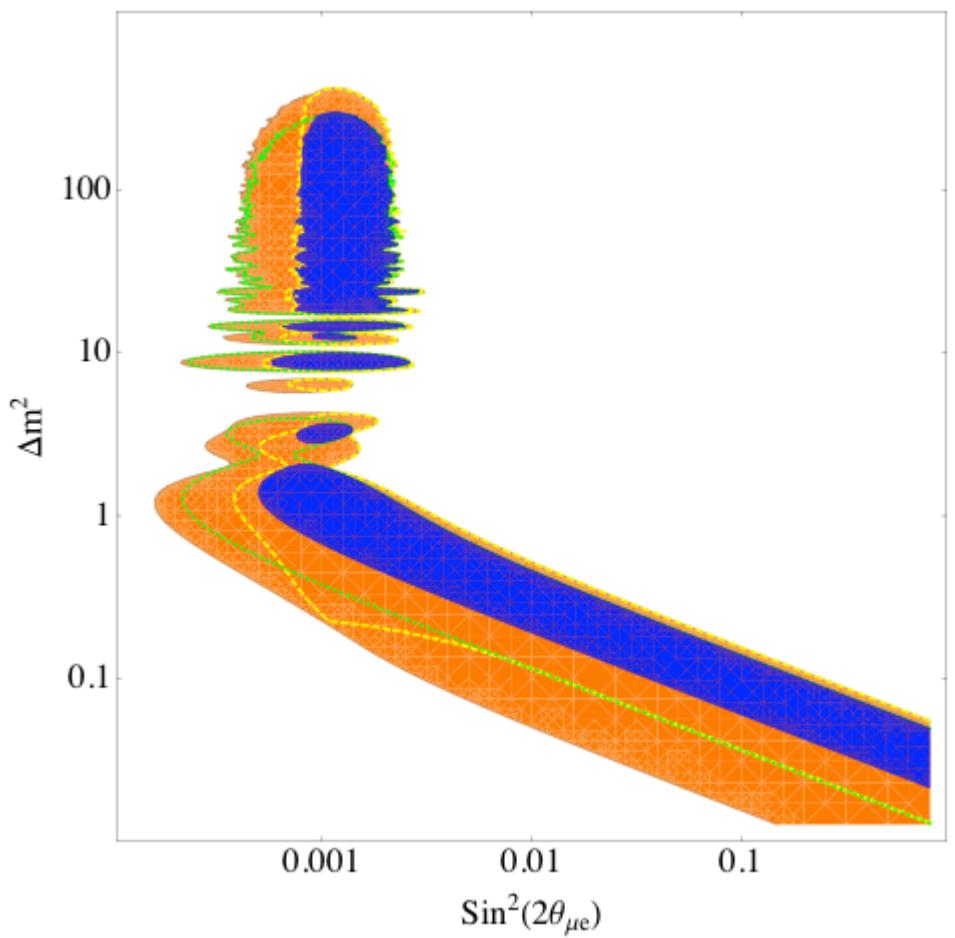
- The MiniBooNE data are consistent with $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations at $\Delta m^2 \sim 1 \text{ eV}^2$ and consistent with the evidence for antineutrino oscillations from LSND.
- The MiniBooNE $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation allowed region appears to be different from the $\nu_\mu \rightarrow \nu_e$ oscillation allowed region. (CP or CPT Violation?)
- The world antineutrino data fit well to a 3+1 oscillation model with $\Delta m^2 \sim 1 \text{ eV}^2$. This model predicts large $\bar{\nu}_\mu$ disappearance.
- MINOS, IceCube, NOvA (two detectors), BooNE at FNAL (two oil Detectors or two LAr detectors), ICARUS at CERN, or OscSNS at ORNL could measure neutrino oscillations with high significance ($>5\sigma$) and prove that sterile neutrinos exist!

Backup

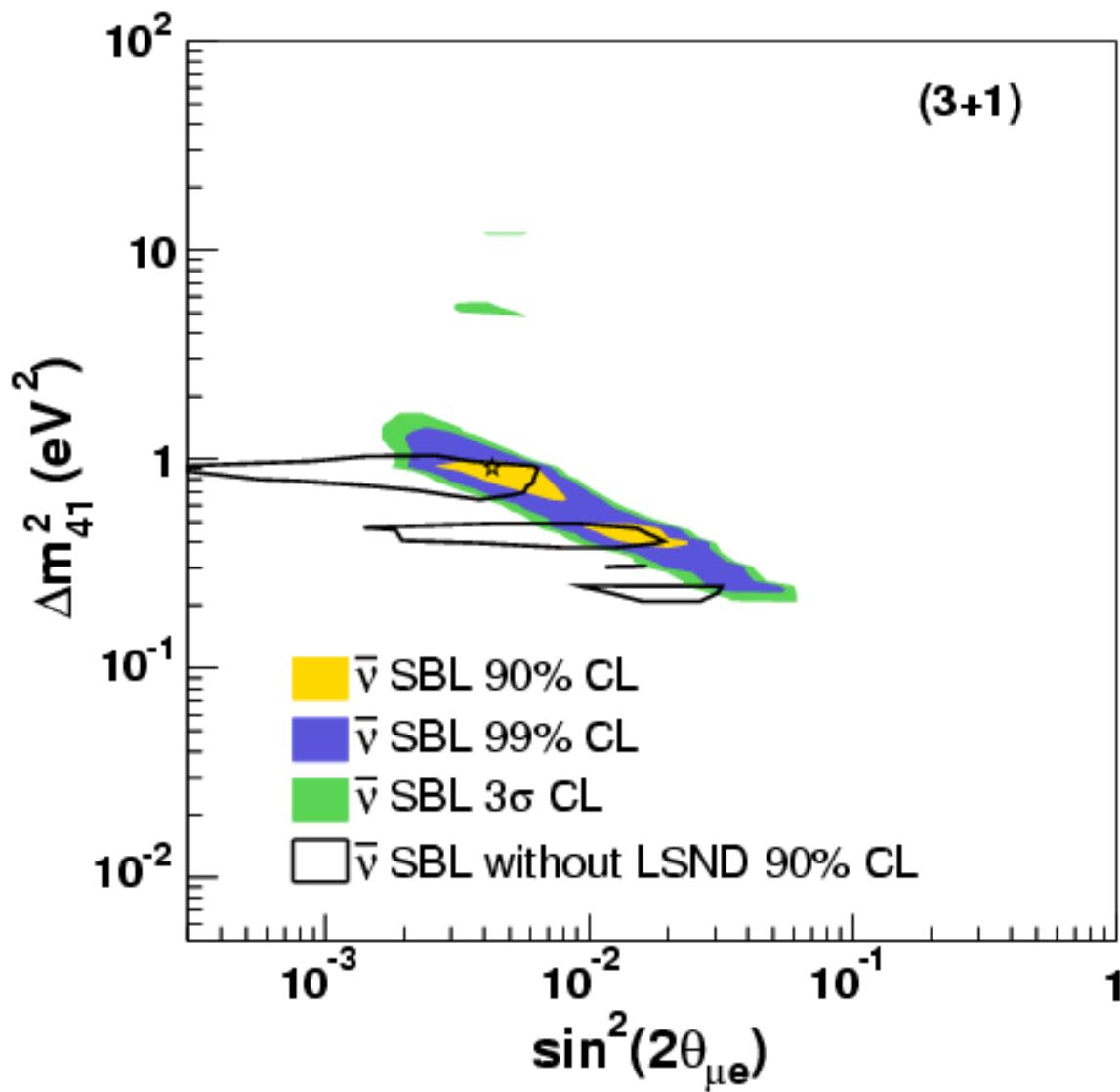
3+2 Global Fit to the World ν & $\bar{\nu}$ Data



Ann Nelson, arXiv: 1010.3970
One light sterile ν (0.1 - 20 eV) &
one heavy sterile ν (33 eV – 40 GeV)



3+1 Global Fit to World Antineutrino Data (with old MiniBooNE data set)

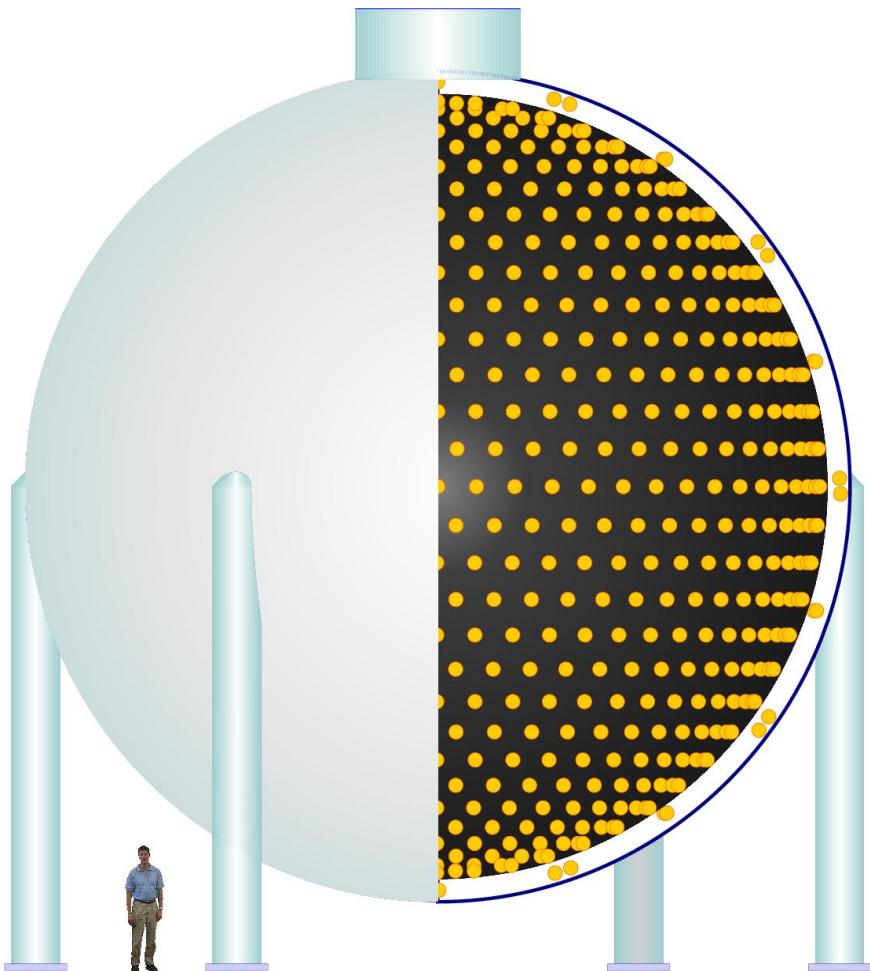


G. Karagiorgi et al.,
PRD80, 073001 (2009)

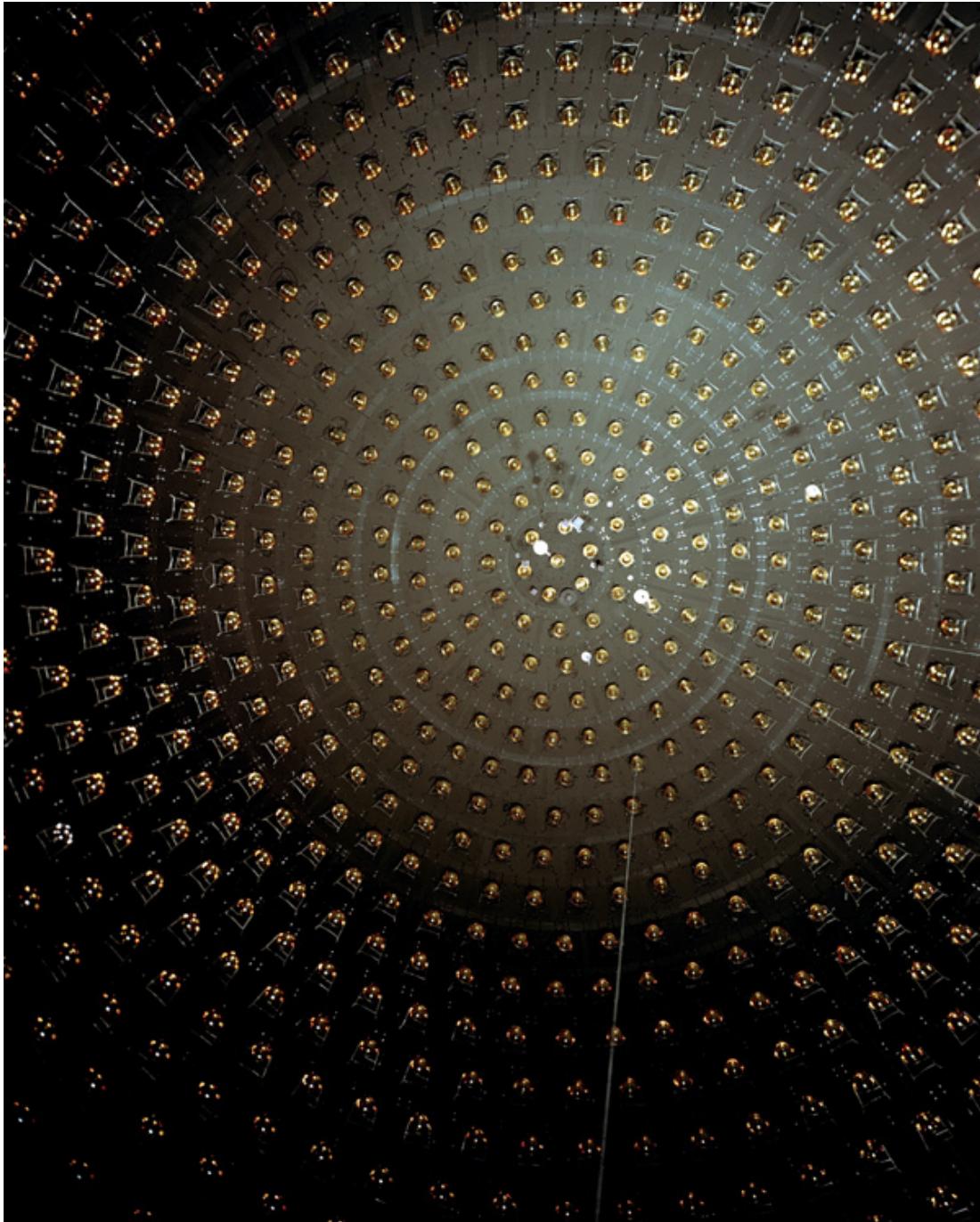
Best 3+1 Fit:
 $\Delta m_{41}^2 = 0.915 \text{ eV}^2$
 $\sin^2 2\theta_{\mu e} = 0.0043$
 $\chi^2 = 87.9/103 \text{ DOF}$
 $\text{Prob.} = 86\%$

Predicts $\bar{\nu}_\mu$ & $\bar{\nu}_e$ disappearance of
 $\sin^2 2\theta_{\mu\mu} \sim 35\%$ and
 $\sin^2 2\theta_{ee} \sim 4.3\%$

The MiniBooNE Detector



- 541 meters downstream of target
- 3 meter overburden
- 12.2 meter diameter sphere
(10 meter “fiducial” volume)
 - Filled with 800 t
of pure mineral oil (CH_2)
(Fiducial volume: 450 t)
 - 1280 inner phototubes,
240 veto phototubes
 - Simulated with a GEANT3 Monte Carlo



10% Photocathode coverage

Two types of
Hamamatsu Tubes:
R1408, R5912

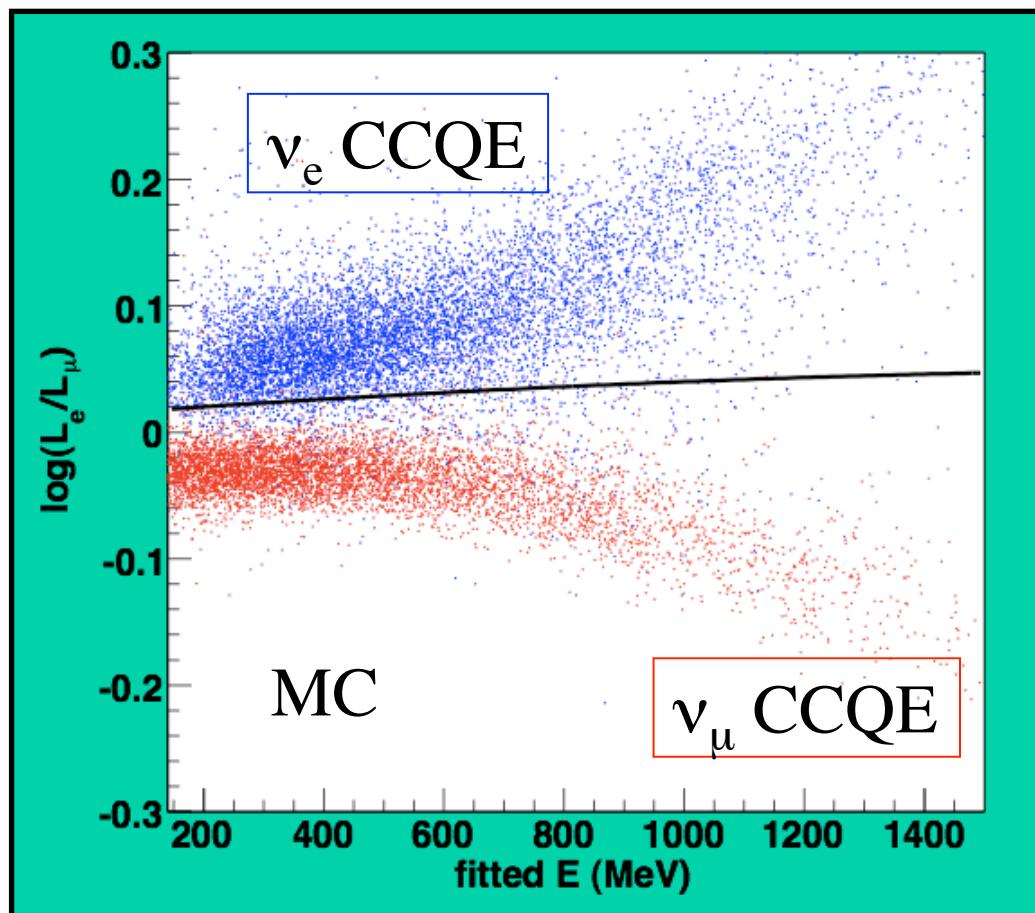
Charge Resolution:
1.4 PE, 0.5 PE

Time Resolution
1.7 ns, 1.1ns



Rejecting “muon-like” events Using $\log(L_e/L_\mu)$

$\log(L_e/L_\mu) > 0$ favors electron-like hypothesis



Note: photon conversions
are electron-like.
This does not separate e/π^0 .

Separation is clean at
high energies where
muon-like events are long.

Analysis cut was chosen
to maximize the
 $\nu_\mu \rightarrow \nu_e$ sensitivity

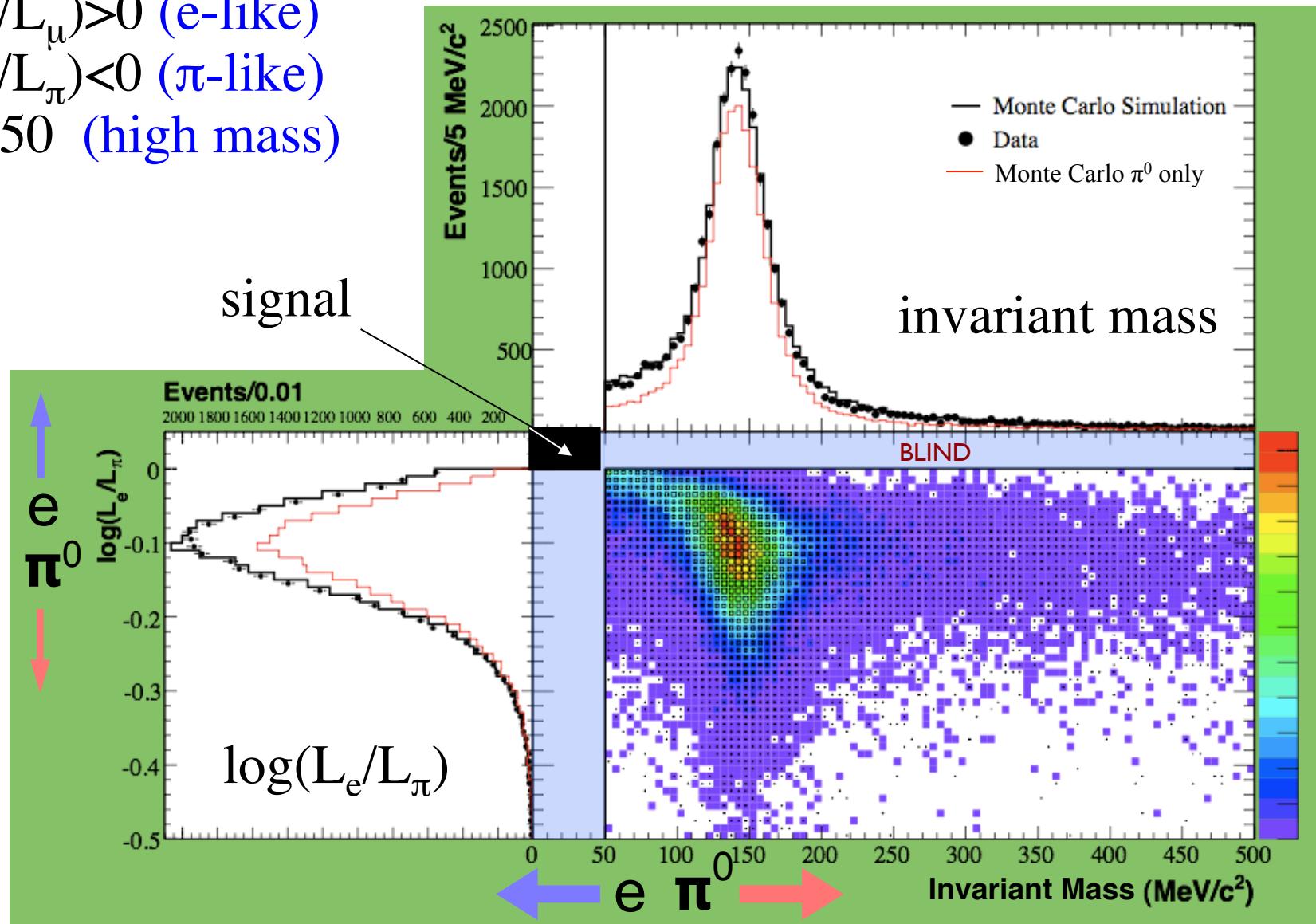
Testing e - π^0 separation using data

1 subevent

$\log(L_e/L_\mu) > 0$ (e-like)

$\log(L_e/L_\pi) < 0$ (π -like)

mass > 50 (high mass)



MiniBooNE Detects Cherenkov Light

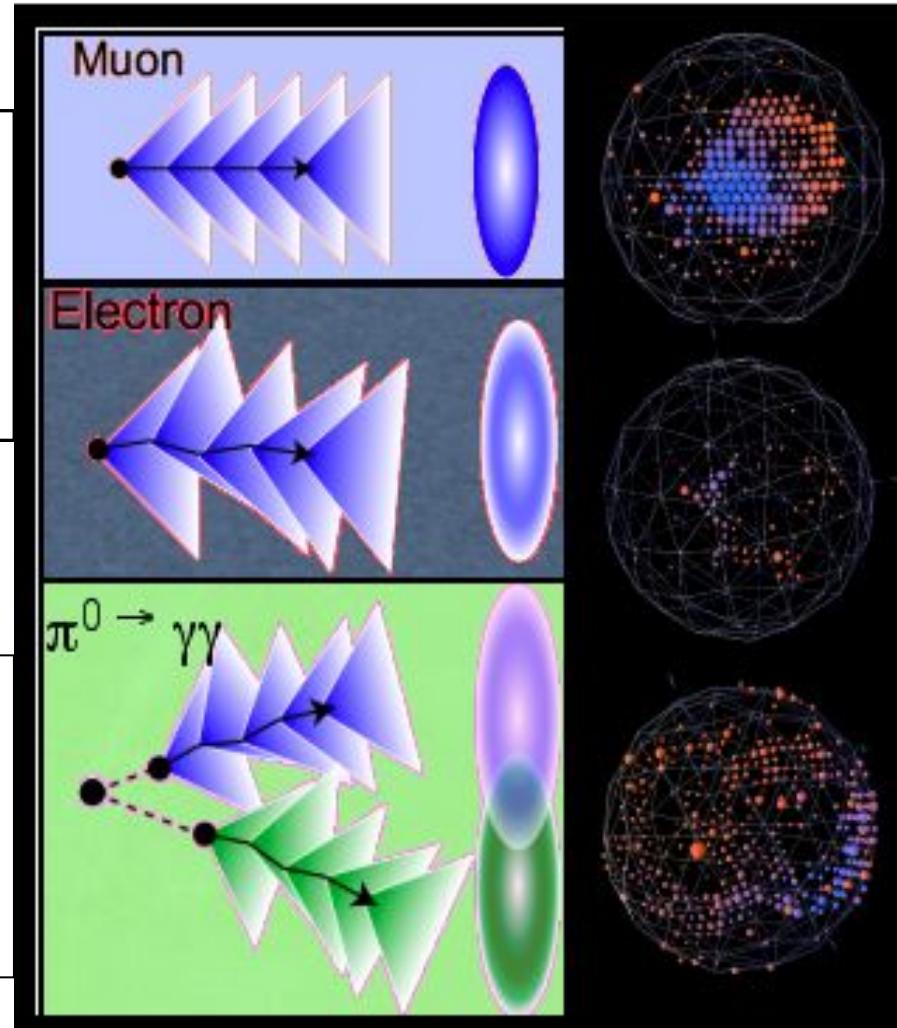
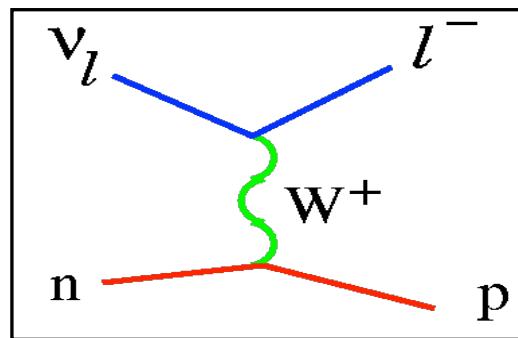
Pattern of Cerenkov Light Gives Event Type

The most important types of neutrino events in the oscillation search:

Background Muons (or charged pions):

Produced in most CC events.

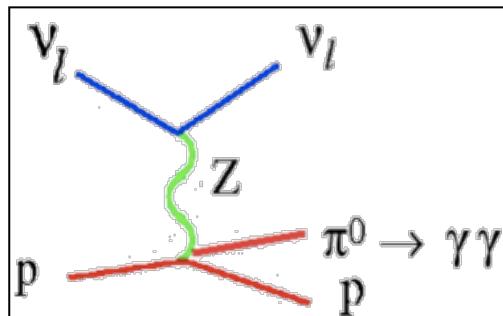
Usually 2 or more subevents
or exiting through veto.



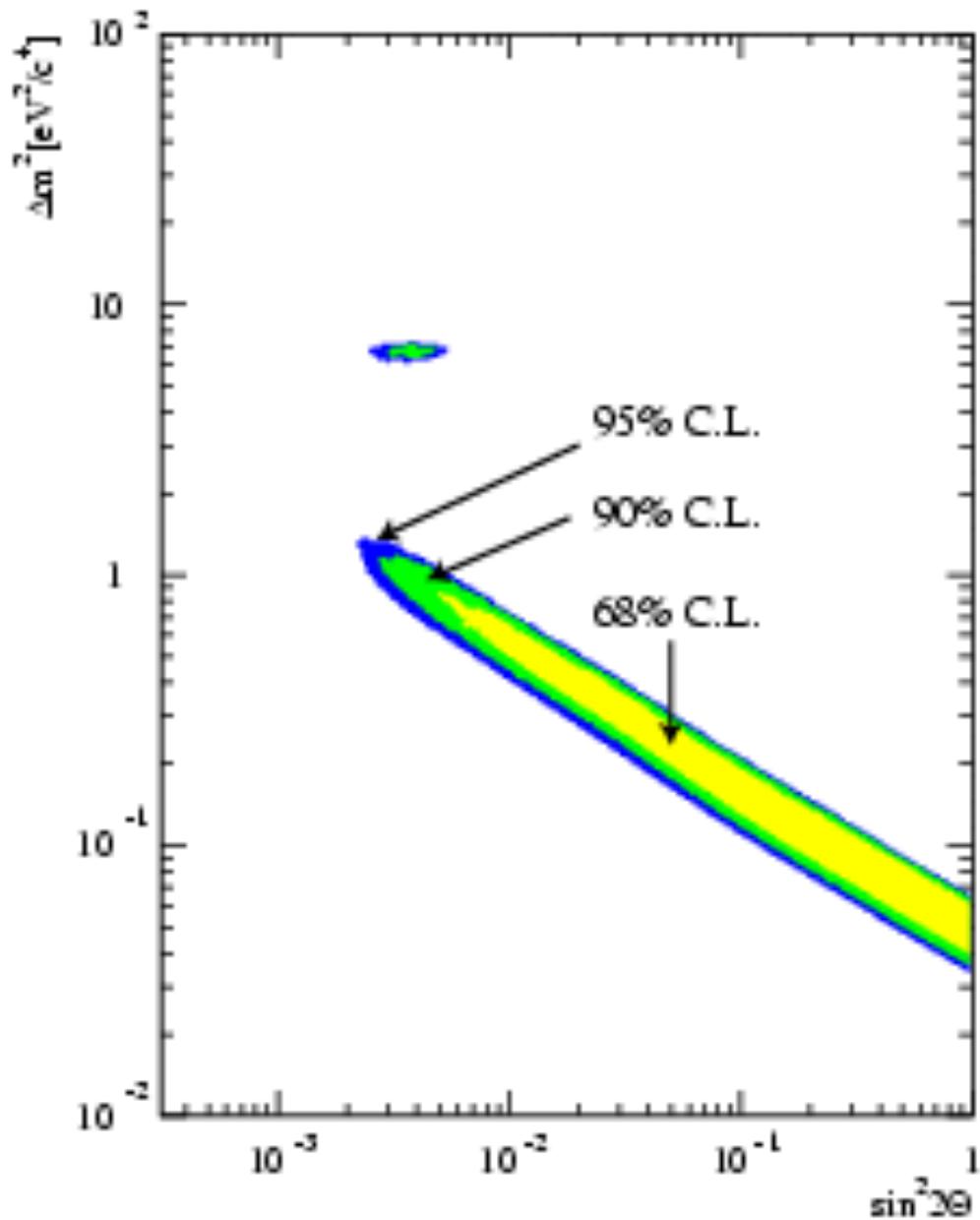
Background π^0 s:

Can form a background if one photon is weak or exits tank.

In NC case, 1 subevent.



Joint LSND/KARMEN Analysis



Joint analysis with
Karmen2: 64% compatible

E. Church, et al., PRD 66, 013001

LSND $\bar{\nu}_e$ Background Estimates

Estimate	$\bar{\nu}_e/\bar{\nu}_\mu$	$\bar{\nu}_e$ Bkgd	LSND Excess
LSND Paper	0.086%	19.5+-3.9	87.9+-22.4+-6.0
Zhemchugov Poster1	0.071%	16.1+-3.2	91.3+-22.4+-5.6
Zhemchugov Poster2	0.092%	20.9+-4.2	86.5+-22.4+-6.2
Zhemchugov Seminar	0.119%	27.0+-5.4	80.4+-22.4+-7.1

All $\bar{\nu}_e$ background estimates assume a 20% error. Note that the $\bar{\nu}_e/\bar{\nu}_\mu$ ratio determines the background!

LSND Paper: A. Aguilar et al., Phys. Rev. D 64, 112007 (2001); (uses **MCNP**)

Zhemchugov Poster1: **FLUKA** $\bar{\nu}_e/\bar{\nu}_\mu$ ratio presented at the ICHEP 2010 Conference, Paris

Zhemchugov Poster2: **GEANT4** $\bar{\nu}_e/\bar{\nu}_\mu$ ratio presented at the ICHEP 2010 Conference, Paris

Zhemchugov Seminar: **FLUKA** $\bar{\nu}_e/\bar{\nu}_\mu$ ratio presented at CERN on September 14, 2010

Although the analysis of Zhemchugov et al. is not fully understood or endorsed, their $\bar{\nu}_e/\bar{\nu}_\mu$ ratios agree reasonably well with the published LSND results.

Note that LSND measures the correct rate of $\bar{\nu}_\mu$ p \rightarrow μ^+ n interactions, which confirms the π^- production and background estimates. Note also, that FLUKA & GEANT4 are not as reliable as MCNP at 800 MeV!